HUMAN FACTORS GOOD PRACTICES IN FLUORESCENT PENETRANT INSPECTION

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1.1 EXECUTIVE SUMMARY

Efficient and effective nondestructive inspection relies on the harmonious relationships among the organization, the procedures, the test equipment, and the human operator. These entities comprise the organization's inspection system to help contribute to continuing airworthiness. The National Transportation Safety Board (NTSB), Federal Aviation Administration (FAA), Transport Canada, and the Civil Aviation Authority (CAA) have all recommended additional studies related to nondestructive inspection.

This research focuses on fluorescent penetrant inspection, especially since the visual nature of the inspection relies heavily on many cognitive, skill, and attitudinal aspects of human performance. This research offers detailed explanation of all human performance challenges related to reliability, profitability of detection, environmental, technical, and organizational issues associated with nondestructive testing.

This research is practical. It describes 86 best practices in nondestructive inspection techniques. The study not only describes the best practices, but also offers tables of explanation as to why each best practice should be used. This listing can be used by industry inspectors.

Finally, the study concludes with research and development needs that have potential to add to the reliability and safety of inspection. The recommendations range from technical improvement, such as scopes for visual inspection, to psychological and performance issues, such as selection, training, and retention.

2.1 INTRODUCTION

This project used accumulated knowledge on human factors engineering applied to Nondestructive Inspection (NDI) of critical rotating engine components. The original basis for this project was the set of recommendations in the National Transportation Safety Board (NTSB) report (N75B/AAR-98/01)[1] concerning the failure of the inspection system to detect a crack in a JT-8D engine hub. As a result Delta Flight 1288 experienced an uncontained engine failure on take-off from Pensacola, Florida on July 6, 1998. Two passengers died. Previous reports addressing the issue of inspector reliability for engine rotating components include the United Airlines crash at Sioux City, Iowa on July 19, 1989 (NTSB/AAR-90/06)[2], and a Canadian Transportation Safety Board (CTSB) report on a Canadian Airlines B-767 failure at Beijing, China on September 7, 1997. Inspection failure in engine maintenance continues to cause engine failures and take lives.

Federal Aviation Administration (FAA) responses to these incidents have concentrated on titanium rotating parts inspection through the Engine and Propeller Directorate (FAA/TRCTR report, 1990, referenced in NTSB/AAR-98/01).[1] These responses have included better knowledge of the defect process in forged titanium, quantification of the Probability of Detection (PoD) curves for the primary NDI techniques used, and drafts of Advisory Circulars on visual inspection (AC 43-XX)[3] and nondestructive inspection (AC 43-ND).[4] Note that nondestructive inspection (NDI) is equivalent to the alternative terminology of nondestructive testing (NDT) and nondestructive evaluation (NDE).

In order to control engine inspection failures, the causes of inspection failure must be found and addressed. Treating the (inspector plus inspection technology plus component) system as a whole, inspection performance can be measured by probability of detection (PoD). This PoD can then be measured under different circumstances to determine which factors affect detection performance, and quantify the strength and shape of these relationships. An example is the work reported by Rummel, Hardy and Cooper (1989)[5] on repeated testing of the same specimens using penetrant, ultrasonic, eddy current and X-ray inspection. Wide differences in PoD were found. It was also noted that many factors affected PoD for each technique, including both technical and inspector factors. Over many years (e.g. Quan and Scott, 1977)[6] a major finding of such studies has been the large effects of the inspector on PoD. Such factors as training, understanding and motivation of the inspector, and feedback to the inspector were considered important.[6]

For rotating parts, the most frequently-applied inspection technique is fluorescent penetrant inspection (FPI). There are some applications of eddy current and ultrasonic inspection, but FPI remains the fundamental technique because it can detect cracks that have reached the surface of the specimen. FPI is also applicable across the whole area of a component, rather than just at a designated point. FPI, to be described in more detail in Section 3.1, can be considered as an enhanced form of visual inspection, where the contrast between a crack and its surroundings is increased by using a fluorescent dye and a developer. It is a rather difficult process to automate, so that the reliance on operator skills is particularly apparent.

In the NDE Capabilities Data Book (Version 3.0, 1997)[7] there is a table showing the importance of different sources of NDI variance for each NDI technique. This table, Table 1, shows the importance of human factors for all non-automated techniques. For FPI, in particular (labeled generically as “Liquid Penetrant” in Table 1), the dominant factors are materials, procedure and human factors. Note that in the NDI literature “human factors” is used as a synonym for “individual inspector factors” rather than in its more technical sense of designing human/machine systems to reduce mismatches between task demands and human capabilities.

Table 1. DOMINANT SOURCES OF VARIANCE IN NDE PROCEDURE APPLICATION

	Materials	Equipment	Procedure	Calibration	Criteria	Human Factors
Liquid Penetrant	X		X			X
Magnetic Particle	X	X	X			X
X-ray	X	X	X			X

Table 1. DOMINANT SOURCES OF VARIANCE IN NDE PROCEDURE APPLICATION						
	Materials	**Equipment**	**Procedure**	**Calibration**	**Criteria**	**Human Factors**
Manual Eddy Current		**X**	**X**	**X**	**X**	**X**
Automatic Eddy Current		**X**	**X**	**X**	**X**	
Manual Ultrasonic		**X**	**X**	**X**	**X**	**X**
Automatic Ultrasonic		**X**	**X**	**X**	**X**	
Manual Thermo -		**X**	**X**	**X**		**X**
Automatic Thermo		**X**	**X**	**X**	**X**	

This project was designed to apply human factors engineering techniques to enhance the reliability of inspection of rotating engine parts. In practice, this means specifying good human factors practice primarily for the FPI technique. Human factors considerations are not new in NDI, but this project provided a more systematic view of the human/system interaction, using data on factors affecting human inspection performance from a number of sources beyond aviation, and even beyond NDI. The aim was to go beyond some of the material already available, such as the excellent checklist "Nondestructive Inspection for Aviation Safety Inspectors" [8] prepared by Iowa State University's Center for Aviation Systems Reliability (CASR).

To summarize, the need for improved NDI reliability in engine maintenance has been established by the NTSB. Human factors has been a source of concern to the NDI community as seen in, for example, the NDE Capabilities Data Book (1997).[7] This project is a systematic application of human factors principles to those NDI techniques most used for rotating engine parts.

3.1 TECHNICAL BACKGROUND: NDI RELIABILITY AND HUMAN FACTORS

There are two bodies of scientific knowledge which must be brought together in this project: quantitative NDI reliability and human factors in inspection. These are reviewed in turn at a level that will allow a methodology to be developed.

3.2 NDI Reliability

Over the past two decades there have been many studies of human reliability in aircraft structural inspection. All of these to date have examined the reliability of Nondestructive Inspection (NDI) techniques, such as eddy current or ultrasonic technologies.

From NDI reliability studies have come human/machine system detection performance data, typically expressed as a Probability of Detection (PoD) curve, e.g. (Rummel, 1998).[9] This curve expresses the reliability of the detection process (PoD) as a function of a variable of structural interest, usually crack length, providing in effect a psychophysical curve as a function of a single parameter. Sophisticated statistical methods (e.g. Hovey and Berens, 1988)[10] have been developed to derive usable PoD curves from relatively sparse data. Because NDI techniques are designed specifically for a single fault type (usually cracks), much of the variance in PoD can be described by just crack length so that the PoD is a realistic reliability measure. It also provides the planning and life management processes with exactly the data required, as structural integrity is largely a function of crack length.

A typical PoD curve has low values for small cracks, a steeply rising section around the crack detection threshold, and level section with a PoD value close to 1.0 at large crack sizes. It is often maintained (e.g. Panhuise, 1989)[11] that the ideal detection system would have a step-function PoD: zero detection below threshold and perfect detection above. In practice, the PoD is a smooth curve, with the 50% detection value representing mean performance and the slope of the curve inversely related to detection variability. The aim is, of course, for a low mean and low variability. In fact, a traditional measure of inspection reliability is the “90/95” point. This is the crack size which will be detected 90% of the time with 95% confidence, and thus is sensitive to both the mean and variability of the PoD curve.

In NDI reliability assessment the model of detecting a signal in noise is one very useful model. Other models of the process exist (Drury, 1992)[13] and have been used in particular circumstances. The signal and noise model assumes that the probability distribution of the detector’s response can be modeled as two similar distributions, one for signal-plus-noise (usually referred to as the signal distribution), and one for noise alone. (This “Signal Detection Theory” has also been used as a model of the human inspector, see Section 3.3). For given signal and noise characteristics, the difficulty of detection will depend upon the amount of overlap between these distributions. If there is no overlap at all, a detector response level can be chosen which completely separates signal from noise. If the actual detector response is less than the criterion or “signal” and if it exceeds criterion, this “criterion” level is used by the inspector to respond “no signal.” For non-overlapping distributions, perfect performance is possible, i.e. all signals receive the response “signal” for 100% defect detection, and all noise signals receive the response “no signal” for 0% false alarms. More typically, the noise and signal distributions overlap, leading to less than perfect performance, i.e. both missed signals and false alarms.

The distance between the two distributions divided by their (assumed equal) standard deviation gives the signal detection theory measure of discriminability. A discriminability of 0 to 2 gives relatively poor reliability while discriminabilities beyond 3 are considered good. The criterion choice determines the balance between misses and false alarms. Setting a low criterion gives very few misses but large numbers of false alarms. A high criterion gives the opposite effect. In fact, a plot of hits (1 – misses) against false alarms gives a curve known as the Relative Operating Characteristic (or ROC) curve which traces the effect of criterion changes for a given discriminability (see Rummell, Hardy and Cooper, 1989).[5]

The NDE Capabilities Data Book (1997)[7] defines inspection outcomes as:

		Flaw Presence	
		Positive	**Negative**
NDE Signal	**Positive**	True Positive No Error	False Positive Type 2 Error
	Negative	False Negative Type 1 Error	True Negative No Error

And defines

$$\text{PoD = Probability of Detection} = \frac{TruePositives}{TruePositives + FalseNegatives}$$

$$\text{PoFA = Probability of False Alarm} = \frac{FalsePositives}{TrueNegatives + FalsePositives}$$

The ROC curve traditionally plots PoD against (1 – PoFA). Note that in most inspection tasks, and particularly for engine rotating components, the outcomes have very unequal consequences. A failure to detect (1 – PoD) can lead to engine failure, while a false alarm can lead only to increased costs of needless repeated inspection or needless removal from service.

This background can be applied to any inspection process, and provides the basis of standardized process testing. It is also used as the basis for inspection policy setting throughout aviation. The size of crack reliably detected (e.g. 90/95 criterion), the initial flaw size distribution at manufacture and crack growth rate over time can be combined to determine an interval between inspections which achieves a known balance between inspection cost and probability of component failure.

The PoD and ROC curves differ between different techniques of NDI (including visual inspection) so that the technique specified has a large effect on probability of component failure. The techniques of ROC and PoD analysis can also be applied to changing the inspection configuration, for example the quantitative study of multiple FPI of engine disks by Yang and Donath (1983).[12]

Probability of detection is not just a function of crack size, or even of NDI technique. Early work by Rummel, Rathke, Todd and Mullen (1975)[39] demonstrated that FPI of weld cracks was sensitive to metal treatment after manufacture. The detectable crack size was smaller following a surface etch and smaller still following proof loading of the specimen. This points to the requirement to examine closely all of the steps necessary to inspect an item, and not just those involving the inspector.

A suitable starting point for such an exercise is the generic list of process steps for each NDI technique. AC43-ND[4] contains flow charts (e.g. their Figure 5.6 for different FPI techniques) shown here as Figure 1. This figure shows the different processes available, although our primary concern here is with the Post Emulsified process, and to a lesser extent with the Water Wash process. A simpler and more relevant list for engine rotating components either process (NDE Capabilities Data Book, P7-3, 1997):[7]

1. Test object cleaning to remove both surface and materials in the capillary opening,
2. Application of a penetrant fluid and allowing a “dwell” time for penetration into the capillary opening,
3. Removal of surface penetrant fluid without removing fluid from the capillary,
4. Application of a “developer” to draw penetrant fluid from the capillary to the test object, surface (the “developer” provides a visible contrast to the penetrant fluid material),
5. Visually inspecting the test object to detect, classify and interpret the presence, type and size (magnitude) of the penetrant indication. (NOTE: Some automated detection systems are in use and must be characterized as special NDE processes).

The nature of this NDE method demands attention to material type, surface condition and rigor of cleaning. It is obvious that processes that modify surface condition must be applied after penetrant processing has been completed. Such processes include, conversion coatings, anodizing, plating, painting, shot peening, etc. In like manner, mechanical processes that “smear” the surface and close capillary openings must be followed with “etch” and neutralization steps before penetrant processing. Although there is disagreement on the requirement for etching after machining processes for “hard materials,” experimental data indicate that all mechanical removal processes result in a decrease in penetrant detection capabilities.

This set of steps and the associated listing of important factors affecting detection performance provides an excellent basis for the subsequent application of human factors knowledge in conjunction with NDI reliability data to derive good practices for engine NDI.

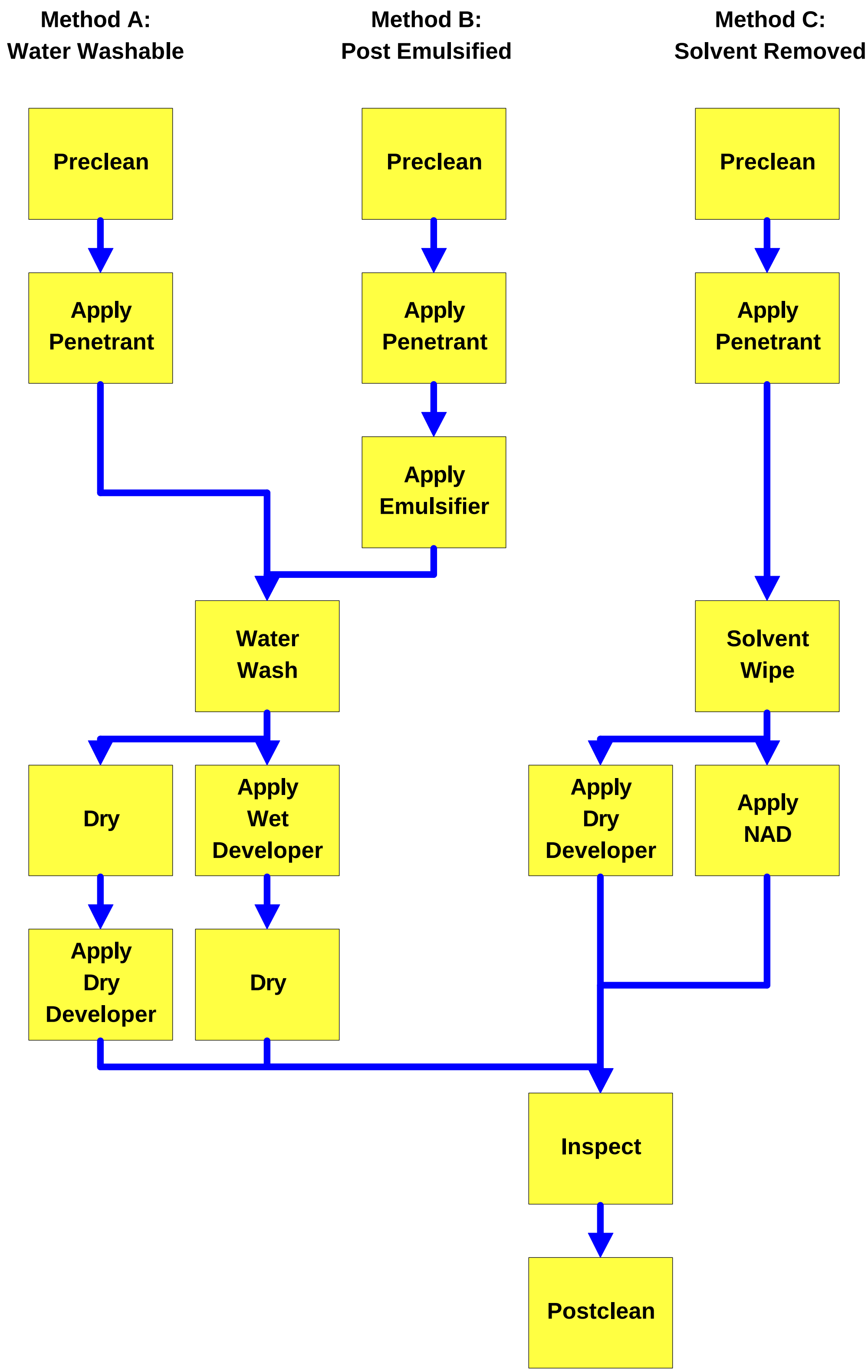

Figure 1. FPI process flow charts, adapted from AC 43-ND, Figure 5.6

3.3 Human Factors in Inspection

Note: There have been a number of recent book chapters covering this area,[13,14] which will be referenced here rather than using the original research sources.

Human factors studies of industrial inspection go back to the 1950's when psychologists attempted to understand and improve this notoriously error-prone activity. From this activity came literature of increasing depth focusing an analysis and modeling of inspection performance, which complemented the quality control literature by showing how defect detection could be improved. Two early books brought much of this accumulated knowledge to practitioners: Harris and Chaney (1969)[15] and Drury and Fox (1975).[16] Much of the practical focus at that time was on enhanced inspection techniques or job aids, while the scientific focus was on application of psychological constructs, such as vigilance and signal detection theory, to modeling of the inspection task.

As a way of providing a relevant context, we use the generic functions which comprise all inspection tasks whether manual, automated or hybrid.[13] Table 2 shows these functions, with an example from fluorescent penetrant inspection. We can go further by taking each function and listing its correct outcome, from which we can logically derive the possible errors (Table 3). Humans can operate at several different levels in each function depending upon the requirements. Thus in Search, the operator functions as a low-level detector of indications, but also as a high-level cognitive component when choosing and modifying a search pattern. It is this ability which makes humans uniquely useful as self-reprogramming devices, but equally it leads to more error possibilities. As a framework for examining inspection functions at different levels the skills/rules/knowledge classification of Rasmussen (1983)[17] will be used. Within this system, decisions are made at the lowest possible level, with progression to higher levels only being invoked when no decision is possible at the lower level.

Table 2. Generic Task Description of Inspection Applied to Fluorescent Penetrant Inspection

Function	Description
1. Initiate	All processes up to visual examination of component in reading booth. Get and read workcard. Check part number and serial number. Prepare inspection tools. Check booth lighting. Wait for eyes to adapt to low light level.
2. Access	Position component for inspection. Reposition as needed throughout inspection.
3. Search	Visually scan component to check cleaning adequacy. (Note: this check is typically performed at a number of points in the preparation and inspection process.) Carefully scan component using a good strategy. Stop search if an indication is found.
4. Decision	Compare indication to standards for crack. Use re-bleed process to differentiate cracks from other features. Confirm with white light and magnifying loupe.
5. Response	If cleaning is below standard, then return to cleaning. If indication confirmed, then mark extent on component. Complete paperwork procedures and remove component from booth.

Table 3. Generic Function, Outcome, and Error Analysis of Test Inspection		
Function	**Outcome**	**Logical Errors**
Initiate	Inspection system functional, correctly calibrated and capable.	1.1 Incorrect equipment 1.2 Non-working equipment 1.3 Incorrect calibration 1.4 Incorrect or inadequate system knowledge
Access	Item (or process) presented to inspection system	2.1 Wrong item presented 2.2 Item mis-presented 2.3 Item damaged by presentation
Search	Individuals of all possible non-conformities detected, located	3.1 Indication missed 3.2 False indication detected 3.3 Indication mis-located 3.4. Indication forgotten before decision
Decision	All individuals located by Search, correctly measured and classified, correct outcome decision reacted	4.1 Indication incorrectly measured/confirmed 4.2 Indication incorrectly classified 4.3 Wrong outcome decision 4.4 Indication not processed
Response	Action specified by outcome decision taken correctly	5.1 Non-conforming action taken on conforming item 5.2 Conforming action taken on non-conforming item

For most of the functions, operation at all levels is possible. Presenting an item for inspection is an almost purely mechanical function, so that only skill-based behavior is appropriate. The response function is also typically skill-based, unless complex diagnosis of the defect is required beyond mere detection and reporting.

3.3.1 Critical Functions: search and decision

The functions of search and decision are the most error-prone in general, although for much of NDI, setup can cause its own unique errors. Search and decision have been the subjects of considerable mathematical modeling in the human factors community, with direct relevance to FPI in particular.

In FPI, visual inspection and X-ray inspection, the inspector must move his/her eyes around the item to be inspected to ensure that any defect will eventually appear within an area around the line of sight in which it is possible to have detection. This area, called the visual lobe, varies in size depending upon target and background characteristics, illumination and the individual inspector's peripheral visual acuity. As successive fixations of the visual lobe on different points occur at about three per second, it is possible to determine how many fixations are required for complete coverage of the area to be searched.

Eye movement studies of inspectors show that they do not follow a simple pattern in searching an object. Some tasks have very random appearing search patterns (e.g., circuit boards), whereas others show some systematic search components in addition to this random pattern (e.g., knitwear). However, all who have studied eye movements agree that performance, measured by the probability of detecting an imperfection in a given time, is predictable assuming a random search model. The equation relating probability (p_1) of detection of an imperfection in a time (t) to that time is

$$p_t = 1 - \exp\left(-\frac{t}{\bar{t}}\right)$$

where $\bar{t}$ is the mean search time. Further, it can be shown that this mean search time can be expressed as

$$\bar{t} = \frac{t_o A}{apn}$$

where

t_o	= average time for one fixation
A	= area of object searched
a	= area of the visual lobe
p	= probability that an imperfection will be detected if it is fixated. (This depends on how the lobe (a) is defined. It is often defined such that p = ½. This is an area with a 50% chance of detecting an imperfection.
n	= number of imperfections on the object.

From these equations we can deduce that there is speed/accuracy tradeoff (SATO) in visual search, so that if insufficient time is spent in search, defects may be missed. We can also determine what factors affect search performance, and modify them accordingly. Thus the area to be searched (A) is a direct driver of mean search time. Anything we can do to reduce this area, e.g. by instructions about which parts of an object not to search, will help performance. Visual lobe area needs to be maximized to reduce mean search time, or alternatively to increase detection for a given search time. Visual lobe size can be increased by enhancing target background contrast (e.g. using the correct developer in FPI) and by decreasing background clutter (e.g. by more careful cleaning before FPI). It can also be increased by choosing operators with higher peripheral visual acuity[18] and by training operators specifically in visual search or lobe size improvement.[19] Research has shown that there is little to be gained by reducing the time for each fixation, t_o , as it is not a valid selection criterion, and cannot easily be trained.

The equation given for search performance assumed random search, which is always less efficient than systematic search. Human search strategy has proven to be quite difficult to train, but recently Wang, Lin and Drury (1997)[20] showed that people can be trained to perform more systematic visual search. Also, Gramopadhye, Prabhu and Sharit (1997)[21] showed that particular forms of feedback can make search more systematic.

Decision-making is the second key function in inspection. An inspection decision can have four outcomes, as shown in Table 4. These outcomes have associated probabilities, for example the probability of detection is the fraction of all nonconforming items which are rejected by the inspector shown as p_2 in Table 4.

Table 4. Attributes Inspection Outcomes and Probabilities

	True State of Item	
Decision of Inspector	**Conforming**	***Nonconforming***
Accept	Correct accept, p_1	Miss, (1 - p_2)
Reject	False alarm, (1 - p_1)	Hit, p_2

Just as the four outcomes of a decision-making inspection can have probabilities associated with them, they can have costs and rewards also: costs for errors and rewards for correct decisions. Table 5 shows a general cost and reward structure, usually called a "payoff matrix," in which rewards are positive and costs negative. A rational economic maximizer would multiply the probabilities of Table 4 by the corresponding payoffs in Table 5 and sum them over the four outcomes to obtain the expected payoff. He or she would then adjust those factors under his or her control. Basically, SDT states that p_1 and p_2 vary in two ways. First, if the inspector and task are kept constant, then as p_1 increases, p_2 decreases, with the balance between p_1 and p_2 together by changing the discriminability for the inspector between acceptable and rejectable objects. p_1 and p_2 can be changed by the inspector. The most often tested set of assumptions comes from a body of knowledge known as the theory of signal detection, or SDT (McNichol, 1972).[22] This theory has been used for numerous studies of inspection, for example, sheet glass, electrical components, and ceramic gas igniters, and has been found to be a useful way of measuring and predicting performance. It can be used in a rather general nonparametric form (preferable) but is often seen in a more restrictive parametric form in earlier papers (Drury and Addison, 1963).[23] McNichol[22] is a good source for details of both forms.

Table 5. Payoff Matrix for Attributes Inspection

	True State of Item	
Decision of Inspector	**Conforming**	**Nonconforming**
Accept	A	-b
Reject	-c	d

The objective in improving decision making is to reduce decision errors. There can arise directly from forgetting imperfections or standards in complex inspection tasks or indirectly from making an incorrect judgement about an imperfection's severity with respect to a standard. Ideally, the search process should be designed so as to improve the conspicuity of rejectable imperfections (nonconformities) only, but often the measures taken to improve conspicuity apply equally to nonrejectable imperfections. Reducing decision errors usually reduces to improving the discriminability between imperfection and a standard.

Decision performance can be improved by providing job aids and training which increase the size of the apparent difference between the imperfections and the standard (i.e. increasing discriminability). One example is the provision of limit standards well-integrated into the inspector's view of the item inspected. Limit standards change the decision-making task from one of absolute judgement to the more accurate one of comparative judgement. Harris and Chaney (1969)[15] showed that limit standards for solder joints gave a 100% performance improvement in inspector consistency for near-borderline cases.

One area of human decision-making which has received much attention is the vigilance phenomenon. It has been known for half a century that as time on task increases, then the probability of detecting perceptually-difficult events decreases. This has been called the vigilance decrement and is a robust phenomenon to demonstrate in the laboratory. Detection performance decreases rapidly over the first 20-30 minutes of a vigilance task, and remains at a lower level as time or task increases. Note that there is not a period of good performance followed by a sudden drop: performance gradually worsens until it reaches a steady low level. Vigilance decrements are worse for rare events, for difficult detection tasks, when no feedback of performance is given, and where the person is in social isolation. All of these factors are present to some extent in FPI, so that prolonged vigilance is potentially important here.

A difficulty arises when this body of knowledge is applied to inspection tasks in practice. There is no guarantee that vigilance tasks are good models of inspection tasks, so that the validity of drawing conclusions about vigilance decrements in inspection must be empirically tested. Unfortunately, the evidence for inspection decrements is largely negative. A few studies (e.g. for chicken carcass inspection)[24] report positive results but most (e.g. eddy current NDI)[25,26] find no vigilance decrement.

It should be noted that inspection is not merely the decision function. The use of models such as signal detection theory to apply to the whole inspection process is misleading in that it ignores the search function. For example, if the search is poor, then many defects will not be located. At the overall level of the inspection task, this means that PoD decreases, but this decrease has nothing to do with setting the wrong decision criteria. Even such devices as ROC curves should only be applied to the decision function of inspection, not to the overall process unless search failure can be ruled out on logical grounds.

3.4 NDI/Human Factors Links

As noted earlier, human factors has been considered for some time in NDI reliability. This often takes the form of measures of inter-inspector variability (e.g. Herr and Marsh, 1978[27]), or discussion of personnel training and certification.[28] There have been more systematic applications, such as Lock and Strutt's (1990)[29] classic study from a human reliability perspective, or the initial work on the FAA/Office of Aviation Medicine (AAM) Aviation Maintenance and Inspection Research Program project reported by Drury, Prabhu and Gramopadhye (1990).[19] A logical task breakdown of NDI was used by Webster (1988)[30] to apply human factors data such as vigilance research to NDI reliability. He was able to derive errors at each stage of the process of ultrasonic inspection and thus propose some control strategies.

A more recent example from visual inspection is the Sandia National Laboratories (SNL/AANC) experiment on defect detection on their B-737 test bed.[31] The study used twelve experienced inspectors from major airlines, who were given the task of visually inspecting ten different areas. Nine areas were on AANC's Boeing 737 test bed and one was on the set of simulated fuselage panels containing cracks which had been used for the earlier eddy-current study.[25]

In a final example an analysis was made of inspection errors into search and decision errors (Table 6), using a technique first applied to turbine engine bearing inspection in a manufacturing plant.[32] This analysis enables us to attribute errors to either a search failure (inspector never saw the indication) or decision failure (inspector saw the indication but came to the wrong decision). With such an analysis, a choice of interventions can be made between measures to improve search or (usually different) measures to improve decision. Such an analysis was applied to the eleven inspectors for whom usable tapes were available from the cracked fuselage panels inspection task.

Table 6. Observed NDI errors from classified by their function and cause [26]				
Function	**Error Type**	**Aetiology/Causes**	**Miss**	**False Alarm**
3. Search	Motor failure in probe movement	1. Not clamping straight edge 2. Mis-clamping straight edge 3. Speed/accuracy tradeoff	X X X	X
	Fail to search sub-area	1. Stopped, then restarted at wrong point	X	
	Fail to observe display	1. Distracted by outside event 2. Distracted by own secondary task	X X	
	Fail to perceive signal	1. Low-amplitude signal	X	
4. Decision	Fail to re-check area	1. Does not go back far enough in cluster, missing first defect		
	Fail to interpret signal correctly	1. .Marks nonsignals with ? 2. Notes signals but interprets it as noise 3. Mis-classifies signal	 X	X X X
5. Response	Mark wrong rivet	1. Marks between 2 fasteners	X	

The results of this analysis are shown in Table 7. Note the relatively consistent, although poor, search performance of the inspectors on these relatively small cracks. In contrast, note the wide variability in decision performance shown in the final two columns. Some inspectors (e.g. B) made many misses and few false alarms. Others (e.g. F) made few or no misses but many or even all false alarms. Two inspectors made perfect decisions (E and G). These results suggest that the search skills of all inspectors need improvement, whereas specific individual inspectors need specific training to improve the two decision measures.

Table 7. Search and decision failure probabilities on simulated fuselage panel inspection (derived from Spencer, Drury and Schurman, 1996).[31]			
Inspector	**Probability of Search Failure**	**Probability of Decision Failure (miss)**	**Probability of Decision Failure (false alarm)**
A	0.31	0.27	0.14
B	0.51	0.66	0.11
C	0.47	0.31	0.26
D	0.44	0.07	0.42
E	0.52	0.00	0.00
F	0.40	0.00	1.00
G	0.47	0.00	0.00
H	0.66	0.03	0.84
I	0.64	0.23	0.80
J	0.64	0.07	0.17
K	0.64	0.17	0.22

With linkages between NDI reliability and human factors such as these given above, it is now possible to derive a more detailed methodology for this project.

4.1 RESEARCH OBJECTIVES

1. Review the literature on (a) NDI reliability and (b) human factors in inspection.
2. Apply human factors principles to the NDI of engine inspection, so as to derive a set of recommendations for human factors good practices.

5.1 METHODOLOGY

The methodology developed was centered around the issues presented in the previous section. From our knowledge of FPI and human factors engineering, important sources of error could be predicted, and control mechanisms developed for these errors. Data on specific error possibilities, and on current control mechanisms was collected initially in site visits. Each visit was used to further develop a model linking errors to interventions, a process that eventually produced a series of human factors good practices.

5.2 Site Visits

The author, with many colleagues from the FAA's Engine and Propeller Directorate and the NDI community, was actively involved in the NTSB investigation of the Delta Airlines Pensacola accident. During this time we had the opportunity to visit a number of engine repair facilities to analyze their FPI systems. This work has been continued by the Engine and Propeller Directorate, culminating in a 1998 Technical Review.[33] From these investigations have come listings of salient problems which could affect FPI reliability under field conditions. These observations at different sites show a wide variability in the accomplishment of inspection of critical rotating components. In particular, note was made of potential for error in the various stages of fluorescent penetrant inspection (FPI). Cleaning, plastic shot blasting, drying, penetrant application and surface removal, developer application and handling during inspection were all called out for investigation. The close relationship between technical factors affecting probability of detection (e.g. crack still contains oils) and human factors (e.g. lack of process knowledge by cleaners) was noted. The challenge now was to respond to these concerns in a logical and practical manner. The generic function description of inspection (Table 3) and the list of process steps of FPI from the NDE capabilities Handbook were used to structure the methodology.

Visits were made to five engine FPI operations, four at air carriers' facilities and one owned by an engine manufacturer. At each site the author, accompanied by FAA NDI specialists, was given an overview of the cleaning and FPI processes, usually by a manager. At this time we briefed the facility personnel on the purpose of our visit, i.e. to better understand human factors in FPI of rotating engine components rather than to inspect the facility for regulatory compliance. We emphasized that engine FPI was usually a well-controlled process, so that we would be looking for improvements aimed at reducing error potential even further through application of human factors principles.

Following the management overview, the author spent one or two shifts working with personnel in each process. In this way he could observe what was being done and ask why. Notes were made and, where appropriate, photographs taken to record the findings. A particular area of concentration was the reading booth, as this is where active failures can occur (missed indications, false alarms). Usually some rotating titanium components were being processed so that all process stages could be observed while they were performing the most relevant tasks to this study.

Towards the end of the visit the author and FAA colleagues discussed their preliminary data with FPI personnel, typically managers, supervisors and inspectors. Any areas where we could see that a human factors principle could improve their current system were discussed, so that they could take immediate advantage of any relevant findings. Again, the separation of this project from regulatory compliance was emphasized.

5.3 Hierarchical Task Analysis

After each visit, the function analysis of Table 2 was progressively refined to produce a detailed task description of the FPI process. Because each function and process is composed of tasks, which are in turn composed of subtasks, a more useful representation of the task description was needed. A method that has become standard in human factors, Hierarchical Task Analysis (HTA) was used.[34,35] In HTA, each function and task is broken down into sub-tasks using the technique of progressive redescription. At each breakdown point there is a plan, showing the decision rules for performing the sub-tasks. Often the plan is a simple list ("Do 3.1 to 3.5 in order") but at times there are choices and branches. Figure 2 shows the highest level breakdown for FPI, while Figure 3 shows one major process (reading).

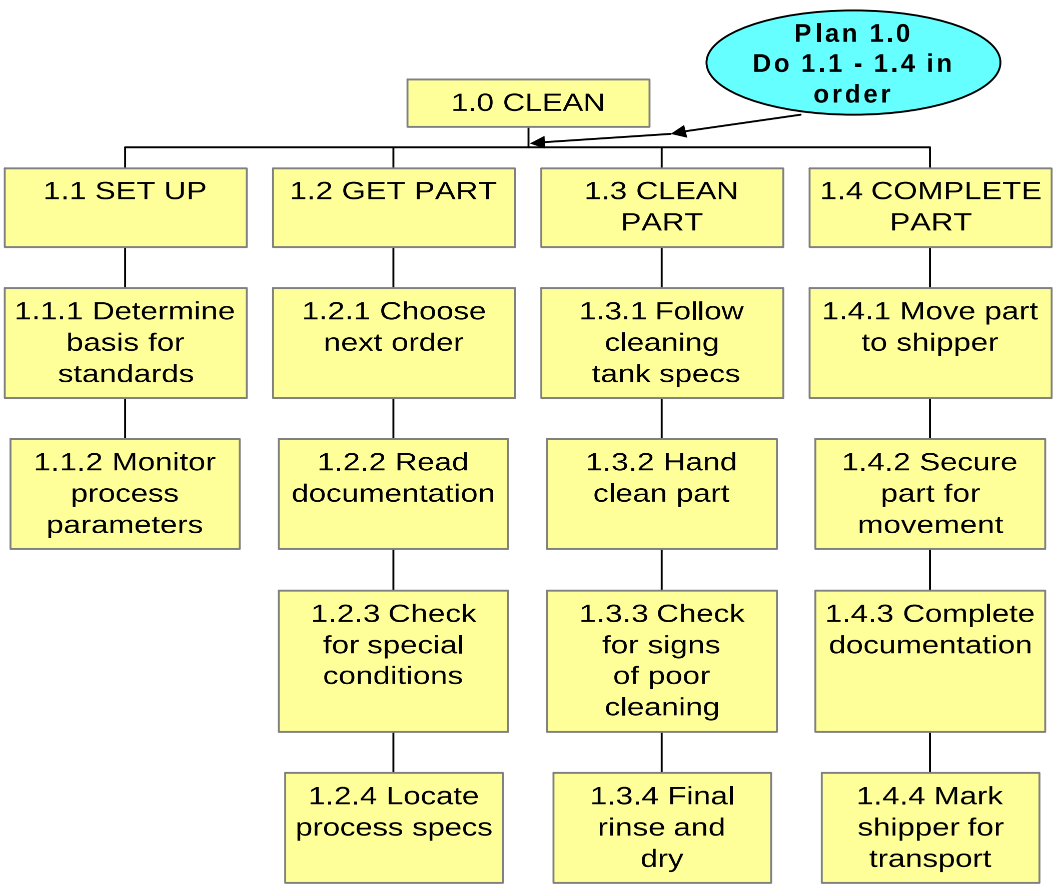

Figure 2. Highest Level Breakdown for FPI

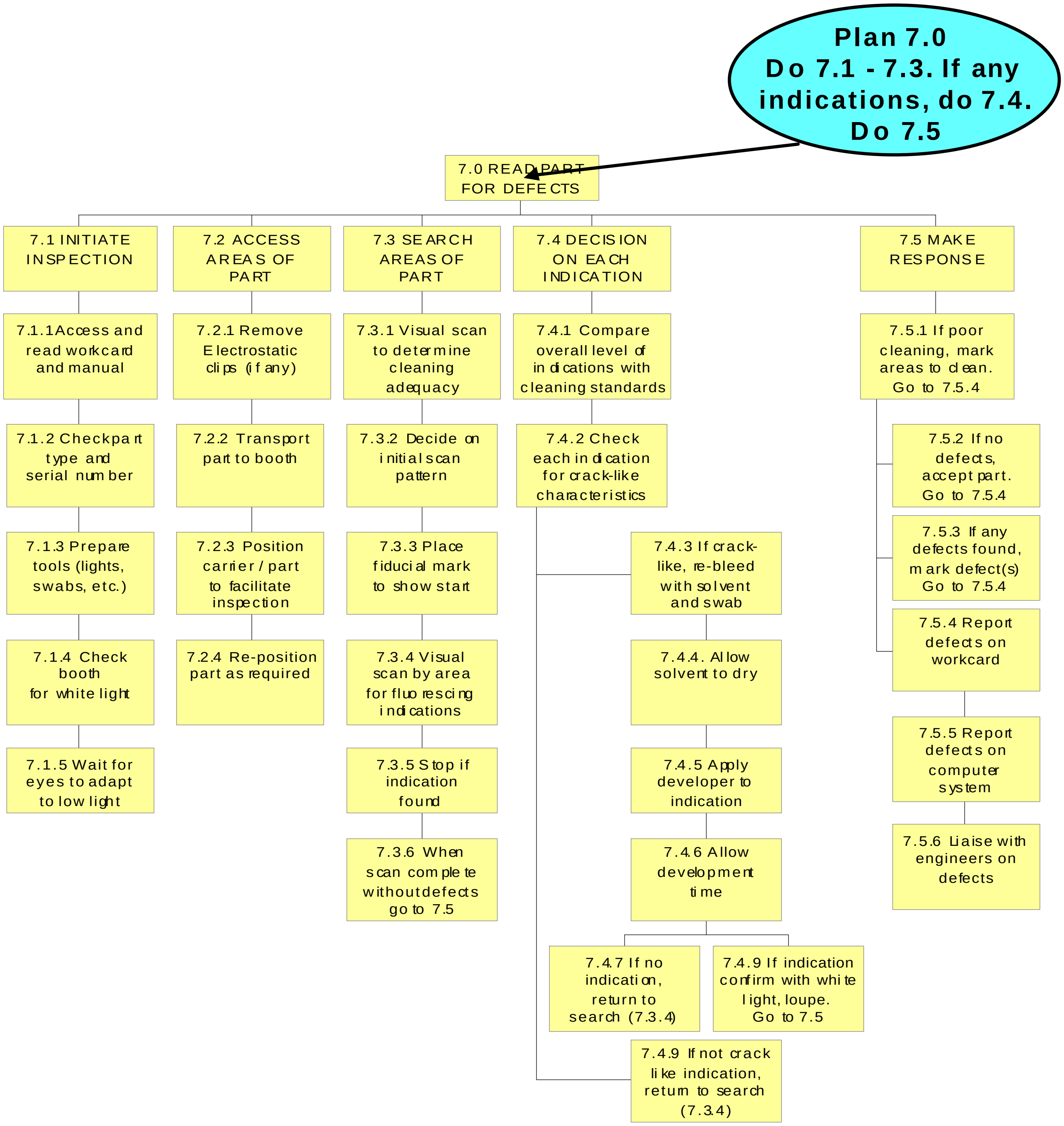

Figure 3. One Major Process (Reading) of the FPI

Each process in FPI is described by Hierarchical Task Analysis (HTA) in Appendix 1. However, the lowest level of redescription is shown in a table accompanying each HTA figure. Each table, for example, that for "3.0 Apply Penetrant" in Table 8, gives the detailed steps, and also asks the questions a human factor engineer would need to answer to ensure that human factors principles had been applied. Note that for the specific task of Apply Penetrant, there are alternative processes using water soluble and post-emulsified penetrant, although only the latter is specified for critical rotating parts in engines.

Finally, for each process in Appendix 1 there is a list of the errors or process variances which must be controlled. Each error is one logically possible given the process characteristics. It can also represent a process variance that must be controlled for reliable inspection performance

This human factors analysis was used to structure each successive site visit so that more detailed observations could be made.

To derive human factors good practices, two parallel approaches were taken. First, direct observation of the sites revealed good practices developed by site management and inspectors. For example, at one site new documentation had been introduced to assist in FPI reading. Components were photographed and labeled on digital images in the document to ensure a consistent nomenclature. At another site, a special holder had been developed for –217 hubs (the component which failed in the Pensacola accident). This holder allowed free part rotation about an inclined axis, which made inspection reading simpler and helped reduce liquid accumulation in pockets during processing.

The second set of good practices came from the HTA analysis. As an overall logic, the two possible outcome errors (active failures) were logically related to their antecedents (latent failures). A point that showed a human link from latent to active failures was analyzed using the HTA to derive an appropriate control strategy (good practice). For example, indications can be missed (active failure) because the eye is not fully adapted to the reading booth illumination. Two causes of this incomplete adaptation were that inspectors underestimate the required adaptation time and overestimate the elapsed time since they were exposed to white light (latent failures). A countdown timer with a fixed interval will prevent both of these effects, thus eliminating these particular latent failures. (Note: inspectors do not have to be idle during this elapsed time—they can perform any tasks which do not expose them to higher luminance levels.)

Two representations of human factors good practice were produced. First, a list of 86 specific good practices is given, classified by process step (Cleaning, Loading, ….., Reading). Second, a more generic list of major issues was produced to give knowledge-based guidance to FPI designer and managers. Here, issues were classified by major intervention strategy (workplace design, lighting, training, etc.) under the broad structure of a model of human factors in inspection. For both representations, the good practices are tied back directly to the active failures they were designed to prevent again to help users understand why an action can reduce errors.

Finally, there are a number of latent failures that will require some additional research to produce direct interventions. These are listed, again with error-based rationales, to give guidance to industry and government research aimed at reducing errors still further.

Table 8. Detailed level of HTA for 3.0 Apply Penetrant		
	TD	**TA**
3.1 Set-up	3.1.1 Monitor penetrant type, consistency (for electrostatic spray) or concentration, chemistry, temperature, level (for tank)	Are measurements conveniently available. Are measurement instruments well human-engineered? Do recording systems require quantitative reading or pass/fail?
3.2 Apply 3.2.1 Electrostatic spray	3.2.1.1 Choose correct spray gun, water washable or post-emulsifiable penetrants available. 3.2.1.2 Apply penetrant to all surfaces.	Are spray guns clearly differentiable? Can feeds be cross-connected? Can sprayer reach all surfaces?
3.2.2 Tank	3.2.2.1 Choose correct tank, water washable or post-emulsifiable penetrants available. 3.2.2.2 Place in tank for correct time, agitating/turning as needed. 3.2.2.3 Remove from tank to allow to drain for specified time.	Are tanks clearly labeled? Is handling system ___________ to use for part placement? Does operator know when to agitate/turn? Does carrier interface with application? Is drain area available?
3.2.3 Spot	3.2.3.1 Choose correct penetrant, water washable or post-emulsifiable penetrants available. 3.2.3.2 Apply to specified areas with brush or spray can.	Are spot containers clearly differentiable? Does operator know which areas to apply penetrant to? Can operator reach all areas with spray can/brush? Is handling systems well human-engineered at all transfer stages?
3.3 Check Coverage	3.3.1 Visually check that penetrant covers all surfaces, including holes. 3.3.2 Return to 3.2 if not complete coverage.	Can operator see penetrant coverage? Is UV light/white light ratio appropriate? Can operator see all of part? Can handling system back up to re-application?
3.4 Dwell Time	3.4.1 Determine dwell time for part. 3.4.2 Allow penetrant to remain on part for specified time.	Does operator know correct dwell time? How is it displayed? Are production pressures interfering with dwell time? Is timer conveniently available, or error-proof computer control?

6.1 RESULTS

Across the whole study, the primary observation was that FPI is underestimated as a source of errors in inspection. The processes observed were usually well-controlled based on written standards, and were clearly capable of finding the larger cracks regularly seen in casings. However, there were still potential errors latent in all of the functions of FPI. Even in a rather traditional process, assumed to be well-understood, errors can still arise, particularly for cracks close to the limits indicated by PoD curves. A number of the facilities had made considerable investment in new equipment and procedures, but the full benefit of these investments can only be realized if the human factors of the process are accounted for. Note that "human factors" is not confined to better training and improved assertiveness by inspectors, although these aspects can be beneficial. Here we use "human factors" to cover all human/system interactions, from physical ergonomics, though environmental effects of lighting and design of equipment for ease of cognitive control, through to improved interpersonal communications.

From our HTA's exhaustive listing of task elements and issues, we can assemble the root causes of detection failure, the primary error we are trying to prevent. Figure 4 shows a fault true analysis with the head event of "defect not reported." Similar fault trees can be conducted with "false alarms" or "delays" as head events, but the results are similar enough that only Figure 4 is presented here to illustrate the logic as failure to detect defects is the primary failure event impacting public safety. Logically, "Defect not reported" can arise because either the defect was not detected, or was detected but not reported. At the next level, these events are further broken down to reveal the underlying root causes or latent failures. Note that at the lowest level there are a number of reoccurring factors, such as training, as well as very specific causal factors, such as poor dark adaptation. This means that interventions to improve the error exposure by utilizing human factors principles will need to be at two levels, the more general and the very specific.

As noted under methodology, these two sets of interventions comprise the main findings of this study. A further set of findings concerns latent failures where there is no obvious current intervention, and hence research is required. This research is not necessarily oriented towards human factors, but the need was shown by the human factors analysis. The following three sections provide the results in detail.

6.2 Detailed Human Factors Good Practices

The direct presentation of human factors good practices is found in Appendix 2. It is given as Appendix 2 because it is so lengthy, with 86 entries. It is organized process-by-process following the HTA in Figure 2 and Appendix 1. For each good practice, there are three columns:

1. **Process**: Which of the seven major processes is being addressed? If the practice cuts across processes (e.g. process logging), it appears in a section "Process Control."
2. **Good Practice**: What is a recommended good practice within each process? Each good practice uses prescriptive data where appropriate, e.g. for bench height. Good practices are written for practicing engineers and managers, rather than as a basis for constructing legally-enforceable rules and standards.
3. **Why?** The logical link between each good practice and the errors it can help prevent. Without the "why" column, managers and engineers would be asked to develop their own rationales for each good practice. The addition of this column helps to train users in applying human factors concepts, and also provides help in justifying any additional resources.

There is no efficient way of summarizing the 86 detailed good practices in Appendix 2: the reader can only appreciate them by reading them. It is recommended that one process, e.g. Reading, is selected first and examined in detail. The good practices should then be checked in turn with each inspector performing the job to find out whether they are actually met. Again, the question is not whether a practice is included in the operating procedures, but whether it is followed for all critical rotating parts by all inspectors. The good practices in Appendix 2 can even be separated and used as individual check items. These can the be sorted into, for example, those which are currently fully implemented, those which can be undertaken immediately, and those which will take longer to implement.

6.3 Broad Human Factors Control Mechanisms

Some issues, and their resulting good practices, are not simple prescriptions for action, but are pervasive throughout the FPI system. For example, "Training" appears many times in Figure 4, but good human factors practice clearly goes beyond the prescription for a certain number of hours of classroom instruction plus an additional number of hours of on-the-job training. Human factors good practice in training considers the knowledge and skills to be imparted for the many different tasks of FPI. The specific needs for error free completion of "Apply Penetrant" will necessarily be quite different from those of "Read Component."

In this section we consider four control mechanisms which impact human factors causes of error in FPI. We present those concerned with (1) individual abilities (training, selection, turnover), (2) hardware design, (3) software design (job aids, environment design) and (4) the managerial environment. Note that this report does not go into depth on the background of each control mechanism, as background material is readily available on each. *The Human Factors Guide for Aviation Maintenance 3.0*[36] is one readily accessible source of more information. This is available at the HFAMI web site: www.hfskyway.com, or on the annual Human Factors in Aviation Maintenance and Inspection CD-ROM, available from FAA/AAM. An additional more general source is the ATA Spec 113 Human Factors Programs,[37] available on the ATA's web site: www.air-transport.org

6.3.1 Operator Selection, Training and Turnover

Most engine FPI inspectors are highly experienced individuals. The job is a steady one, with predictable tasks, and generally confined to one or two shift operations. Thus, it becomes a desirable posting and attracts high-seniority inspectors. Among this group, turnover is usually relatively low, giving a stable workforce that have had time to understand and trust each other's abilities. Selection is often not an issue at major air carriers, as seniority among qualified applicants often determines who is selected. At regional carriers and repair stations selection is typically less restricted. Individual visual capabilities are rarely assessed beyond "eyesight" which is typically a measure of visual acuity at the central portion of the visual field (foveal acuity), and is only one visual aspect affecting inspection performance. Foveal acuity has not been shown to be a good predictor of inspection performance: acuity in the outer areas of the visual field (periphiral acuity) is usually a better predictor[13].

In contrast, the cleaning operation is usually separate from FPI, and is often an entry-level operation. Cleaning personnel do not need an A&P license and so the cleaning process is a first step into aviation maintenance and inspection for some recruits. Note that FPI inspectors do not need such a license either, but they must have other extensive qualifications such as Level 2 of Level 3 NDI. For others, it is a relatively well-paying job with schedules convenient for other concerns, such as education or family responsibilities. Turnover is typically much higher than in FPI.

Special programs are needed to ensure that entry-level cleaners obtain the background knowledge needed to operate intelligently. Such training programs are not general practice throughout the industry, although the ATA and FAA are currently working on training for cleaning personnnel. Some organizations have brought cleaners into closer contact with their customers, the FPI inspectors, by having them work as helpers in the FPI shop. Others have instituted programs of "internships" with brief periods in other areas of the engine facility designed to promote understanding of *why* rules and procedures are important. This is a useful and necessary complement to their training in the rules themselves, and represents a good practice from a human factors' viewpoint.

In cleaning, there is also the issue of management turnover. There was wide variation across facilities, and even across shifts, in the job tenure of cleaning managers and supervisors. In some facilities, the supervisory and managerial positions were seen as training and proving grounds for upwardly-mobile personnel, whereas in others the same manager had been in place for many years. Experience is important in providing both technical and human leadership, so that if high turnover among supervisory and management of cleaning is normal, well-developed training and mentoring programs are needed to bring new hires up to an effective level rapidly. Many of the potential errors that are found in cleaning areas would have been visible to more experienced managements, and hence eliminated before we found them.

The training needs for inspection personnel are more complex than for cleaners. From Figure 4, training needs arise at many points in the process. For each process step before Reading, the training needs are basically procedural, to ensure that metal-to-metal contact is avoided, that components are completely covered by penetrant, etc. But the Reading function is the essence of FPI, and requires training programs derived from knowledge of human factors in inspection. There are specific ways of training search and decision functions. These are rarely adequate in the mandated combination of classroom and on-the-job training (OJT) followed by most facilities. For example, most inspectors had devised different search procedures for different components. When asked how they had arrived at these procedures, some said they had copied an older inspector while others had devised their own. This would not matter if search procedures were all equally effective, but they are not. We observed areas of incomplete coverage, e.g. of dovetails, as well as areas missed after an interruption such as application of developer or confirming an indication with white light. Effective search for aircraft inspection can be taught, e.g. Gramopadhye, Drury and Sharit (1997),[21] and needs to be taught in FPI.

One area of more difficulty is in the training of expectations. Inspectors need to know, and actively seek, information on where cracks or other defects are most likely on components. Thus, over time, they build up an expectation of what type of indications arise in which locations on components. Weld cracks are one specific example. A more general rule is that cracks will occur in areas of high stress concentration, such as abrupt shape changes or radii. These expectations help inspectors to formulate efficient search strategies by starting search where cracks are most likely. These expectations are reinforced when cracks are found. If a crack is rare on a component, other inspectors will be called in to see the indication, leading to shared expectations and contributing to training. Any means of sharing data, such as photographs or messages from other facilities or OEM's will make the expectation more realistic. This process should be seen as part of a continuous feedback or continuous training system and be used as a good practice for all inspectors no matter how experienced.

Expectations can, however, mislead inspectors. Throughout aviation there is a tendency for inspectors to have "favorite" defects and locations based on their expectations. If their expectations are perfect, this will lead to excellent performance, but they may not always be perfect. For example, if an inspector spends an inordinate fraction of inspection time looking where defects are expected, then other areas may be neglected. While inspectors intend to search all areas of a component, they may have a difficult task in detecting a defect where it is not expected. Thus, training must continuously reinforce searching with equal diligence where defects are technically possible but not expected.

6.3.2 Hardware Design

For an FPI system the most obvious human factors hardware principles are to prevent metal-to-metal contact for rotating parts, and to ensure a compatible human-equipment interface.

Preventing metal-to-metal contact is a matter of listing the ways in which critical rotating parts can contact metal objects, and eliminating each one. Many examples are listed in Appendix 2, from covering inspection aids such as UV light with protective coatings or guards to designing conveyor systems which make contact difficult or impossible. Note that initial design is not the only critical factor: protective coatings must be maintained; operators must be trained.

Good hardware interface design is covered in detail in human factors and ergonomics handbooks. Two aspects predominate in FPI: design of controls/displays to reduce errors and design of workstations for operator comfort. It seems obvious that controls for lighting, conveyor movement and water valves should be within easy reach of the operator and well labeled. However, even the newest designs we visited showed that the operator was not always the main consideration in design. Water valves were at knee height, control panels required walking to the end of the line, timers could only be set from outside the spray booth and so on. Labeling ranged from nonexistent (a bank of six electrical switches with no labels; water baths that were not labeled as they did not contain hazardous materials) through inadequately labeled (spray guns with approved hazardous materials stickers, but with the name of the substance handwritten on the label) to excellent (clear up and down arrows on a hoist).

In addition, controls should move in the natural direction, i.e. in the same sense as the controlled object. Switches should go down to lower a component into a liquid tank; room brightness controls should turn clockwise to increase light level and so on. Again, we found some installations that did not follow human population stereotypes. Poor placement, labeling and design of controls will increase human error rate, leading to mis-reading of dials or movement of components backwards instead of forward. They can also cause operators to take short cuts, such as not switching on the UV lighting because it is a walk to the control panel, or just glancing at a knee-high pressure gauge and recording “pass” in the log book. Such errors are small, but we are now at the point where we need to eliminate them to make progress on process reliability.

Finally, good ergonomics is important to task performance, even inspection. Most sites visited already had comfortable and adjustable chairs for inspectors. Some sites negated their value because the component hanger did not allow ease of raising, lowering and rotating so that the inspector could not sit down to perform the task. Note that comfortable posture improves inspection performance and does not, as some think, make the inspector less vigilant.[38] (Some ergonomic fixes are obvious: at one site, the inspection table was at normal desk height (about 1.0m), but so much material was stored under the bench that the knees of a seated inspector could not fit under it. The inspector in fact ignored the chair and performed the whole inspection bending over the component on the bench—a most uncomfortable and unsafe posture, and a posture that will increase the error rate of inspection. As with the design of controls and displays, the required good practices have been in ergonomics textbooks for many years. It is time to use them consistently in FPI. Also under the heading of good ergonomics comes the design of the part support hardware. This may be a fixture hanging from an overhead conveyor or a fixture on an inspection bench. In either case, the fixture must allow convenient repositioning of the part so that all areas are easily visible and accessible during reading. Any fixtures used should also allow water and other liquids to drain completely and not pool on the part.

6.3.3 Software and Job Aids

"Software" can refer to literally computer programs, or to paper-copy procedures and documents which control the FPI process. They are both a form of job aid, although that term is usually reserved for separate tools and assistive devices.

Procedures were usually designed and presented as work control cards, known variously as workcards, shop travelers or routing sheets. They were primarily work control devices concerned with ensuring that components were correctly identified and routed through the processes. Thus, they contained component number and serial number, a sequential list of processing departments (Cleaning, FPI, etc.), and a space for signing off each activity. Similar systems were in place for computer-based control, although most sites retained the paper system alongside the computer system.

Any detail on <u>how</u> to perform the procedures was contained in a manual in the cleaning and FPI departments. This was always available for FAA inspection, and the training program usually ensured that it had been read by trainees. There was no evidence at most sites that this documentation played any part in the day-to-day activities of experienced inspectors. In fact, at most sites the inspector's role was to locate and mark indications, while the decisions about each indication were made remotely by engineers or managers. Thus, much of the detail in the manuals concerning the critical sizes of rejectable indications would be of no interest to inspectors.

This reliance on the high level instructions on the routing sheet (e.g. "FPI per process XXX") meant that all knowledge about what to inspect for, where to concentrate search and what defects had been found previously was retained only in the memory of the individual inspector. A better way is to actively capture the knowledge from all sources to produce a documentation aid that is of real value during the inspection process. One site had developed workcards (computer-based) with photographs of each part labeled to show specific features. Unfortunately, the written information hardly varied from document to document, and so was not of great use of inspectors. In fact, at no time did we observe an inspector actually consulting these excellent job aids.

A solution is to ensure that wisdom from all inspectors and external sources is captured and used in the documentation. If each inspector can contribute their own "pet defects," and this data can be combined with OEM and industry information, the documents can become living and evolving job aids. They should be the first place an inspector turns to when in the reading booth, just as workcards for heavy checks in airframe inspection (C-checks, D-checks) are used routinely as part of the task. The aim should be to support the inspectors with job aids they will want to use.

Any sharing of information by inspectors can be useful, and is already a part of the communications environment common throughout NDI. Detecting rare, small cracks is not easy and any help from internal and external sources can be expected to improve detection performance.

6.3.4 Interpersonal System Design

Relationships between the various people and groups within engine maintenance and inspection can have a large impact on defect detection performance. As seen in Figure 4, even if an indication has been located and detected, it may not always be reported. The good practices are considered which impact on FPI reliability: management pressures, shift work/overtime, and cleaning/FPI relationships.

At many of the sites, the FPI inspectors were not the final decision authority for indications. As noted earlier, their role was to locate and mark indications which were later interpreted by engineers or others in the engine repair system. These decisions were made under white light with a magnifying loupe (usually) using the manual as a source of standards for rejection. Sometimes the FPI inspectors were involved with this decision, but often they were not. Inspectors questioned not being kept informed, and suspected pressures not to reject components. Whether or not such pressure in fact exists, the relationship between the FPI inspectors and their down-stream colleagues needs improvement at some sites. Open communication and 100% outcome feedback would do much to prevent frictions arising.

In a rather similar way, the FPI inspectors are the downstream judges of the quality of cleaning. Appendix 2 lists a number of good practices centered around relationships between cleaning and FPI. Joint training is one good practice: an equitable mechanism for returning components for re-cleaning is another. Again, any feedback to the cleaners should be 100% and not just the return of poorly-cleaned items. It would help communications if both FPI and cleaning reported to the same manager, so that any problems between the departments could be dealt with locally and rapidly. At many sites, this was not the case, forcing inspection management to either go far up the command chain or devise informal return procedures. FPI cannot function without effective cleaning, so that both departments need to ensure that their missions are indeed closely aligned.

One area of human factors concern that has often been successfully addressed is the issue of overtime/shift work. Most engine FPI shops visited work only one or two shifts so that the problems of vigilance caused by diurnal rhythms of inspectors would not be as likely to affect performance as they are for airframe inspectors who at times have to work multiple shifts back-to-back. But back-to-back shifts are not uncommon in facilities where overtime is a desirable privilege for extra payment. In such facilities, excessive working hours need to be discouraged to avoid vigilance decrements arising from cumulative fatigue. This could be a particular problem for engine FPI as the variety of inspection environment and product is much less than would be found for airframe inspection.

At the sites visited, shift turnover did not appear to be a problem as each shift tried to ensure that there were no partially-inspected components at shift change. There could be a hidden shift turnover problem where the inspector on one shift sends a part back for cleaning, which is done on the following shift. In such a case, the original inspector is not available to clarify the cleaning problems with the new shift's cleaning personnel, leading to possible cleaning errors. At one site, however, a large difference was noted in ambient lighting between shifts. One shift used overhead lights throughout the FPI process while the other did not. Generally, the lower the light level outside of UV-lit areas, the more rapidly and completely inspectors' eyes adapt.

6.3.5 Environmental Issues

Both the visual environment and the physical environment are a source of human factors good practices. The first was mentioned above (dark adaptation) and the second similarly has managerial overtones: visual control.

The human eye adapts rather rapidly to lower luminance levels at first, but the process slows down. For photoptic (color) vision, about a 10 minute adaptation of the cones in the retina are required. After 10 minutes, the eye is about 10 times as sensitive (1 log unit). About half of this adaptation takes place in about 3 minutes. The eye can further adapt using the rods in the retina, a process taking a further 25 minutes or so and giving a 100-fold increase in sensitivity. This second level of adaptation is rarely required for FPI.

Note that adaptation time is the time to recover from any relatively bright white-light exposure. This can come from opening of the reading booth, use of a white light for confirming an indication, or even looking at a bright computer screen. Even a brief white-light exposure will require the same adaptation time. The inspectors we met were convinced that times such as 3-10 minutes for adaptation did not apply to them, as they only needed about one minute to adapt. Even then, they over-estimated the time spent in the dark and often started inspecting well before a true one minute had elapsed.

If an inspector begins FPI reading before a reasonable level of dark adaptation has been achieved, the probability of detection will suffer seriously, particularly for small cracks. Management control is required here, with three potential solutions:

1. Train inspectors in the dark adaptation curve. This can easily be demonstrated with a vision test in the darkened booth, where each minute of adaptation will be seen to produce improved detection performance.
2. Provide a simple “adaptation timer” set at an agreed adaptation time, and help inspectors to use this job aid before starting inspection. Note that inspectors do not need to be idle during the adaptation time. They can perform any tasks, such as preparation, which do not expose them to high luminance levels and which do not require detection of small defects.
3. Provide a vision test sheet in the booth so that an inspector can check the dark adaptation after each bright light exposure. This can be wall mounted at a fixed distance from the inspector’s working point.

Note that many items fluoresce under UV light in the reading booth, such as clothing, paper or even workcards. Fluorescence is the transformation of UV energy into energy within the visual spectrum. Thus, anything that fluoresces brightly in the reading booth is effectively another white light exposure. Management control and training should be used to minimize these sources of white light and glare that will reduce the visibility of small indications.

Visual control is a management principle based on the fact that the simplest way to control items is to be able to see them easily. In FPI, this principle applies to control of unapproved items in any part of the process, but particularly in the reading booth. At some sites the unapproved items were solvents which had not been approved. In the visual environment context, they would be shirts that fluoresce. Either case can benefit from visual control, i.e. by reducing the number of items in the reading booth so that inspectors and management can see instantly that only the small number of approved job aids are present. At various sites we saw reading booths used as storage areas, hence cluttered with irrelevant (and often unapproved) objects. In others, each booth was “home” to one inspector, and used for meal breaks and rest breaks. We all have a tendency to personalize our “own” workplace, but this is not a good idea in a reading booth. This is no place for lunch bags, radios, newspapers, etc. Before such practices are eliminated, management must provide alternate break and rest areas that are equally attractive.

7.1 RESEARCH AND DEVELOPMENT NEEDS

A number of points have arisen in this project where the human factors analysis has revealed control needs which cannot be addressed directly from current practice. All of them area centered on the function of reading the component. These are listed here, in no particular order.

7.2 Improved Solvent and NAD

Recently, the solvents used by inspectors for re-bleeding indications have changed in response to environmental concerns. These concerns must be respected, but the change has introduced a large error potential into the visual search process. When an indication is re-tested by swabbing it with solvent, the inspector must wait for the solvent to dry before confirming the indication. Drying times on the solvent labels are about one minute or more. During visual search, the inspector must either:

1. Re-bleed the indication and wait for the approved time to elapse before confirming.
2. Re-bleed the indication and continue the search process during the drying time, returning to the indication for confirmation when the time has elapsed.

In practice, the inspectors tend to confirm the indication before the full time has elapsed, as they do not like to be "idle." Or they continue the search and forget either where the indication was or where their new search has reached. Both lead to potential errors of missed indications. A real danger is that inspectors will resort to solvent re-bleeding less frequently than they should because both of the approved procedures are disruptive and error prone. There is an urgent need to develop solvents that are rapid-acting and environmentally friendly.

The non-aqueous wet developer (NAD) suffers from exactly the same problem of time delay, and hence is subject to the same errors. Again, a more rapid-acting NAD would be of great benefit in reducing the potential for these errors.

7.3 Better Magnifying Loupe

Most inspectors have available 5X or 10X magnifying loupes for visual confirmation of indications. These are not well controlled, and often awkward to use. This is particularly so when the inspector must use two hands to do many tasks: steady the component, hold the light (white or UV) and hold the loupe. An improved loupe would have non-distorting optics, a large eye-relief so that the inspector's eyes do not have to be in a severely-restricted position, and if possible, have hands-free operation. Good loupes are available from the photographic industry where they are used for examining color slides or for focusing images on view cameras. They are not a $10 item! Quality is costly, but loupes last for many years. Many have neck strings, for instant availability. Hands-free operation can be achieved with the flip-down magnifiers which attach to glasses, as used, for example, by dentists. These are instantly available to the inspector, and have the incidental advantage of encouraging the permanent wearing of UV-absorbing spectacles.

A short period of testing, rather than a major research program, will yield more usable magnifying loupes.

7.4 Better TAM Panel Validity

The current process testing samples, called Tool Aerospace Material (TAM) panels, consist of metal coupons with surface cracks of different sizes. These are passed through the process at regular intervals, typically every shift or every day to ensure that the process as a whole is functioning within specifications. Most TAM panels have five areas of surface cracks with graded severity levels. As one is processed, it is read under fluorescent light in the reading booth and the number of areas with visible cracks recorded in the process control log. Either a "pass" is recorded or, better, the number of areas is recorded.

However, a number of problems were seen having more to do with validity than process logging. First, these test panels are notorious for producing positive readings traceable only to residual penetrant in the cracks. It is often possible to demonstrate that developer alone will show visible readings on a supposedly “clean” panel. Poor cleaning is an obvious cause, but there is little confidence among NDI researchers that *any* practical cleaning will remove all traces of prior application of penetrant. We can encourage FPI personnel to persist with thorough cleaning procedures, but a better solution is required. One system available uses disposable one-use panels, but any change of panels means that validity needs to be reestablished, i.e. do “pass” and “fail” criteria accurately predict system performance on cracks found in critical rotating engine parts?

The second issue that needs addressing is also related to panel validity. FPI inspectors admitted that they did not adjust the FPI process when a TAM panel failed to pass the visual test for cracks. A typical reaction was to re-test the system with another panel. This means that the inspectors do not trust the TAM panel system enough to believe its outcome. As a process control technique, it fails to be effective as control actions are not taken based on the outcome.

Either the FPI process is *always* in control, leading to the correct conclusion to discount the test indication, or the test itself does not have the trust of the inspectors. We have no recommended good practices in this area at present, but are raising the issue as one that needs to be addressed.

7.5 Job Aids for Search Strategy

In human visual search, a systematic search strategy is always better than a random strategy in terms of probability of detection (see 3.3.1). Also, a systematic search strategy reduces the probability of forgetting which areas have been searched. In FPI inspection of rotating components, there is often no obvious start point, so that inspectors mark the component to show a chosen start point. But as search progresses, inspectors need to have a simple visual indicator of how far around the component they have searched. This is particularly true when search is interrupted, e.g. for re-bleeding, developer application or white-light confirmation of indications. Many inspectors use one hand to steady the component on its hanger, and use this hand position to indicate which areas have been searched. But they often need to move this hand to reposition the component on to handle other job aids such as the magnifying loupe.

A simple device or mechanism (e.g. erasable pencil) is needed which can rotate around the component, and stay in place when released, to indicate how far around each region search has progressed.

7.6 Realistic Expectation Control

On rotating titanium components, the probability of a crack is very small. Most inspectors will never see such a crack in their working lifetime. From signal detection theory, inspectors will respond to low defect rates by lowering their expectation, and raising their reporting threshold. This is rational behavior, but it means that as cracks become increasingly rare, they become increasingly difficult to detect. We need a means of reversing this tendency.

One mitigating circumstance is that inspectors do not just inspect rotating titanium components. The other things they inspect tend to have higher defect rates, thus helping to keep up their defect expectations. But on these other components, the defects are typically larger than the cracks associated with early stages of rotating titanium component cracking. Thus, inspectors may get a false expectation of defect size. If they only find larger indications, this may reinforce their view that cracks are in fact quite large and easy to detect.

There is little research on how inspectors' expectations are formed and changed, either the absolute expectation level or the expectation as a function of defect size. Equally, there is little research on the effect of such expectations on defect detections and false alarms. Such a program is needed if we are to help inspectors detect rare defects. Note that such a research program will benefit other inspection systems beyond FPI. As processes improve and defects become rarer, so inspectors' expectations will change on any airframe or engine task.

8.1 CONCLUSIONS

This project has combined findings from NDI reliability and human factors in inspection to produce recommendations for human factors good practices in fluorescent penetrant inspection. Recent accidents involving undetected cracks in engine rotating components provide the justification for reliability improvements in FPI. Site visits to a number of engine FPI sites revealed a generally high standard of operations. They also showed many areas where improvements could be made by applying the principles of human factors engineering.

Three sets of recommendations are made in this report. The first is a set of 86 specific good practices arising from the detailed Hierarchical Task Analysis of engine FPI. This list can be used as a checklist for actions by inspectors and managers in FPI. A second list of five more general areas of improvement came from both the HTA and the detailed notes of the site visits. Finally, a set of five research and development needs was generated to provide solutions to currently-unsolved issues.

The methodology used here can be applied to other aspects of engine and airframe inspection beyond FPI of rotating engine components.

9.1 ACKNOWLEDGEMENT

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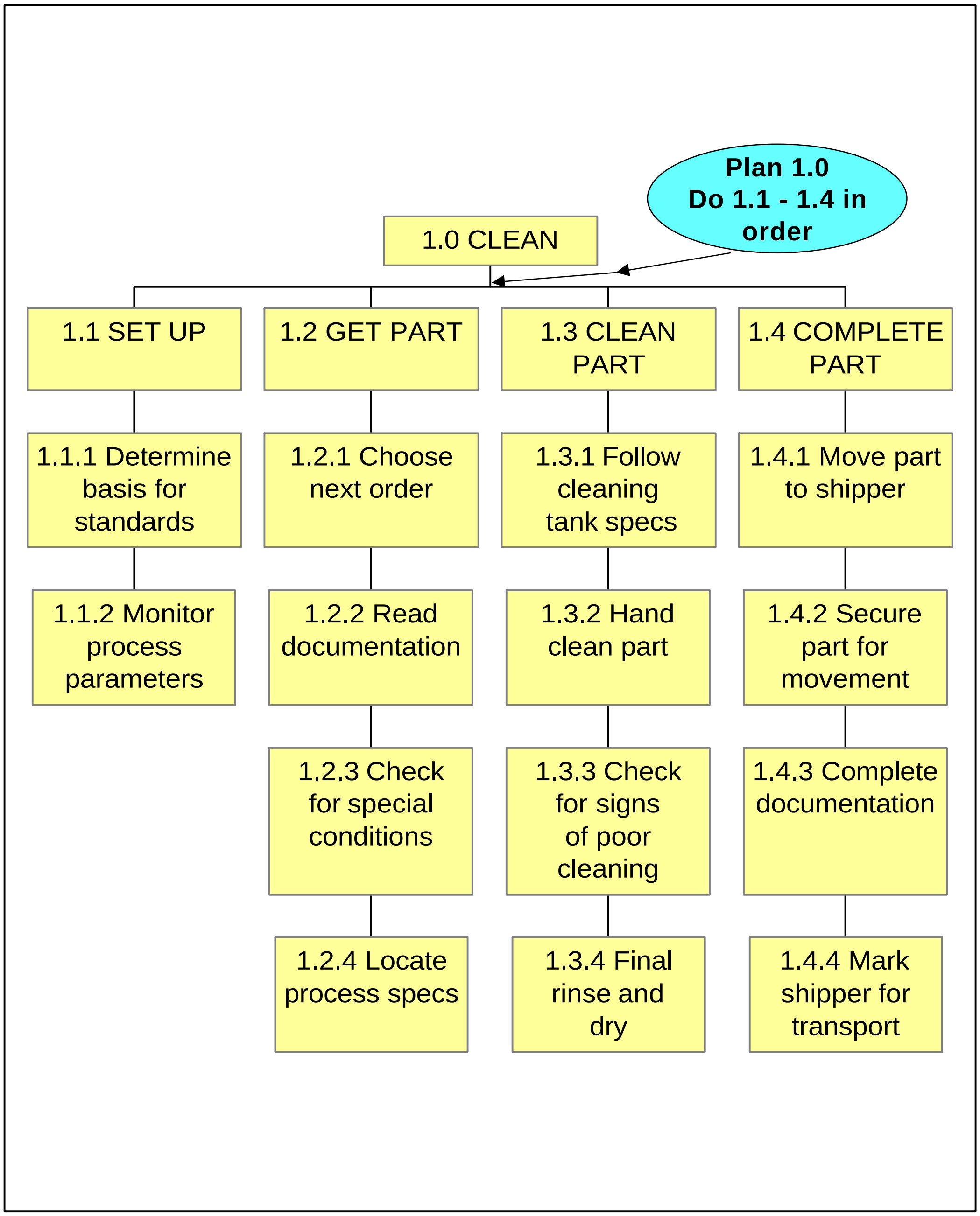
11.1 ACRONYMS

AAM	FAA's Office of Aviation Medicine
AC	Advisory Circular
CAA	Civil Aviation Authority
CASR	Center for Aviation Systems Reliability
CTSB	Canadian Transportation Safety Board
FAA	Federal Aviation Administration
FPI	Fluorescent Penetrant Inspection
HTA	Hierarchical Task Analysis
NAD	Non-Aqueous Wet Developer
NTSB	National Transportation Safety Board
NDI	Nondestructive Inspection
NDE	Nondestructive Evaluation
PoD	Probability of Detection
ROC	Relative Operating Characteristics
SNL/AANC	Sandia National Laboratories
TAM	Tool Aerospace Material

APPENDIX 1

Task description and task analysis of each process in FPI

The overall process is presented first as a top-level key (same as Figure 2). Next, each of the seven processes is presented in detail as an HTA diagram. Finally, each process is presented in the most detailed level as a Task Analysis table.

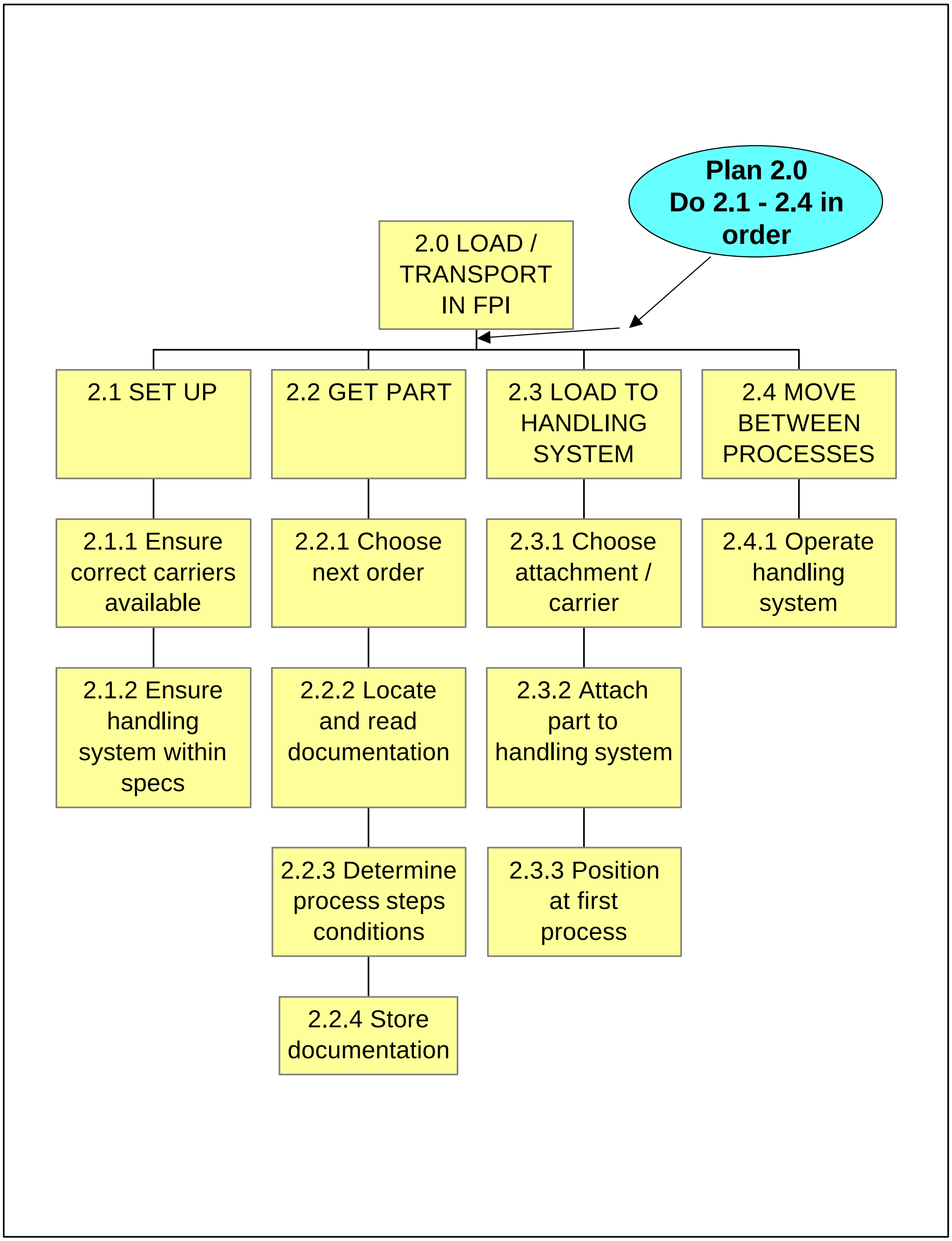


1.0 Cleaning

	Task Description	Task Analysis
1.1 Set-up	1.1.1 Ensure all tanks meet quality standards and regular basis defined in manual. 1.1.2 Monitor levels, temperatures, pressures, composition	Gauges/dials readable? Process log well laid out and available?
1.2 Get part	1.2.1 Choose next order from schedule or availability. 1.2.2 Read documentation, e.g. shop order to find correct process. 1.2.3 Check if special conditions, e.g. returned for marked areas to be re-cleaned. 1.2.4 Locate process specifications to follow.	How well is process schedule defined? Does documentation give unique definition of best process and any acceptable alternatives, if needed? Does documentation have space for special conditions? Is part marked visibly? Does operator understand? Are process specs available? Are process specs used?
1.3 Clean Part	1.3.1 Follow process specifications for sequence and timing of tanks. 1.3.2 Hand clean using specified tools on specified areas of part. 1.3.3 Continue hand cleaning until no visible signs of dirt, oil, dust, scale, coking. 1.3.4 Final rise and dry.	Are times available for each tank? Are times in and out recorded? Are tanks informatively labeled? How does operator find dirt, etc. places to clean? How does operator choose tools? How does operator see signs? How does operator interpret signs? Does operator get feedback which improves performance? Are tools adequate?
1.4 Complete part	1.4.1 Move part back to shipping pallet/container 1.4.2 Secure part for movement. 1.4.3 Complete documentation on cleaning. 1.4.4 Mark container for removal to next process.	Is crane/handling device convenient? Does crane control adequately? Is pallet/container convenient? Are shop order/department log/computer available? Are shop order/department log/computer convenient to use? Can removal operator see and interpret signal?

1.0 Errors/Variances

Wrong part cleaned
Wrong process used
Processes not in specification limits
Insufficient cleaning overall
Insufficient cleaning in specified areas
Part mis-matched with documentation.


Plan 2.0
Do 2.1 - 2.4 in order
2.0 LOAD / TRANSPORT IN FPI
2.1 SET UP
2.2 GET PART
2.3 LOAD TO HANDLING SYSTEM
2.4 MOVE BETWEEN PROCESSES
2.1.1 Ensure correct carriers available
2.2.1 Choose next order
2.3.1 Choose attachment / carrier
2.4.1 Operate handling system
2.1.2 Ensure handling system within specs
2.2.2 Locate and read documentation
2.3.2 Attach part to handling system
2.2.3 Determine process steps conditions
2.3.3 Position at first process
2.2.4 Store documentation

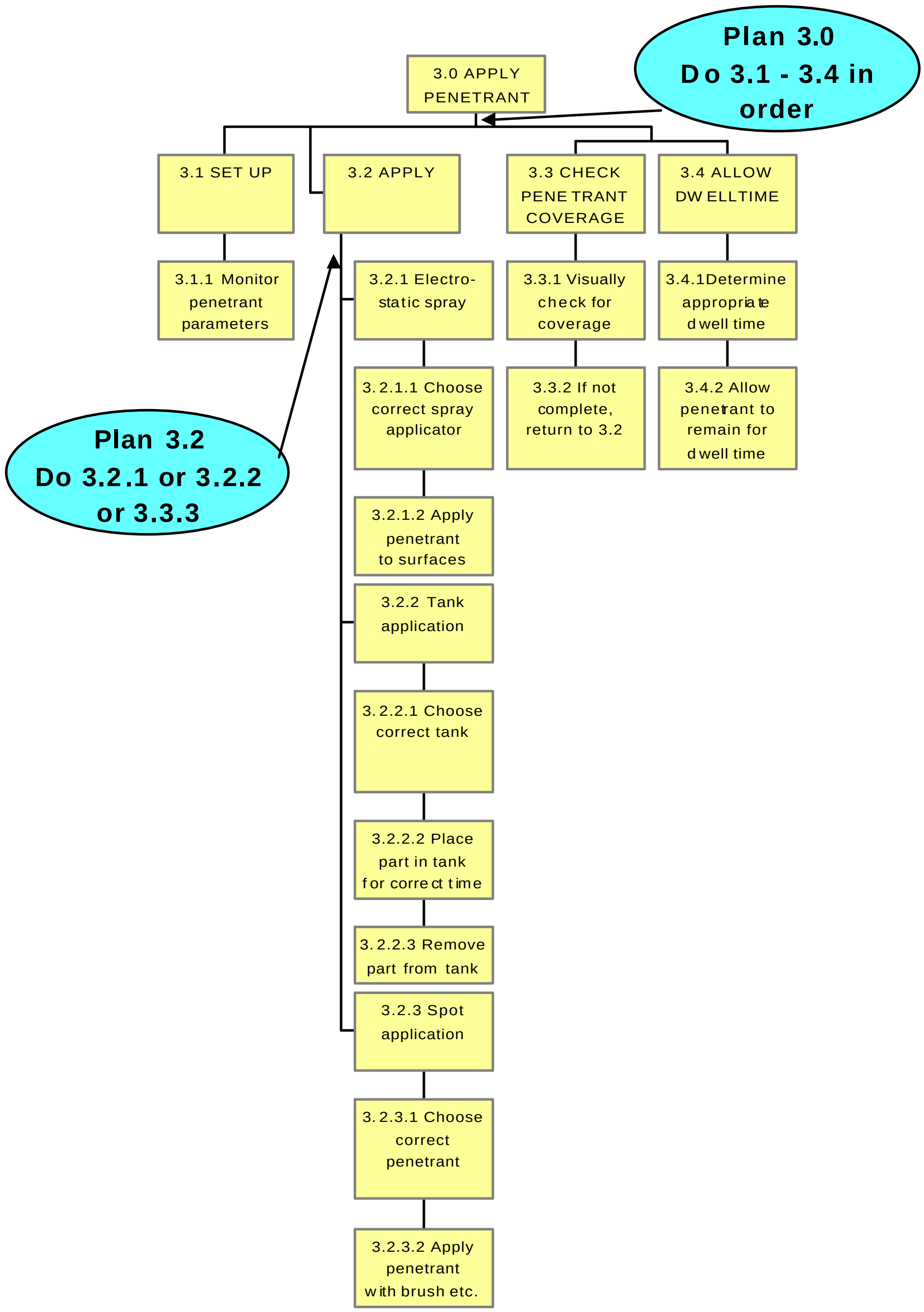
2.0 Load/Transport in FPI

	Task Description	Task Analysis
2.1 Set-up	2.1.1 Ensure proper carriers available (e.g. hooks for overhead conveyor, pallets for roller conveyor) 2.1.2 Ensure conveyor/handling system working within specifications.	Carriers must avoid metal-to-metal contact, particularly sliding contact. Carriers must be clean to ensure no contamination of part, and to prevent fluorescence of carrier in reading booth. Handling system must ensure part is not dropped or allowed to hit other object.
2.2 Get part	2.2.1 Choose next order from schedule or input query. 2.2.2 Locate and read documentation, e.g. shoporder. 2.2.3 Read documentation to determine process steps. 2.2.4 Store part documentation so that it can be re-united with part at any time, but especially for reading.	How are parts scheduled? Does operator know? Is documentation easy to use? Are process steps specified explicitly? Are process steps same for all parts? How are documents stored? How are parts related to documents?
2.3 Load to handling system	2.3.1 Choose attachment/carrier 2.3.2 Attach part to handling system. 2.3.3 Position at first process.	Are carriers clean? Do carriers avoid metal to metal content? Can carrier prevent process from reaching part? Can carrier allow cross-contamination of processes? Is handling system well human-engineered?
2.4 Move between processes	2.4.1 Operate handling system as appropriate to move between processes.	Is handling systems well human-engineered at all transfer stages?

2.0 Errors/Variances

Handling system allows part damage.
Handling system allows cross-contamination.
Handling system not well human engineered (cause of ½).

Carries unsuitable.
Documents not available for process/not used.
Documents not well-designed.
Errors in matching parts to documents.

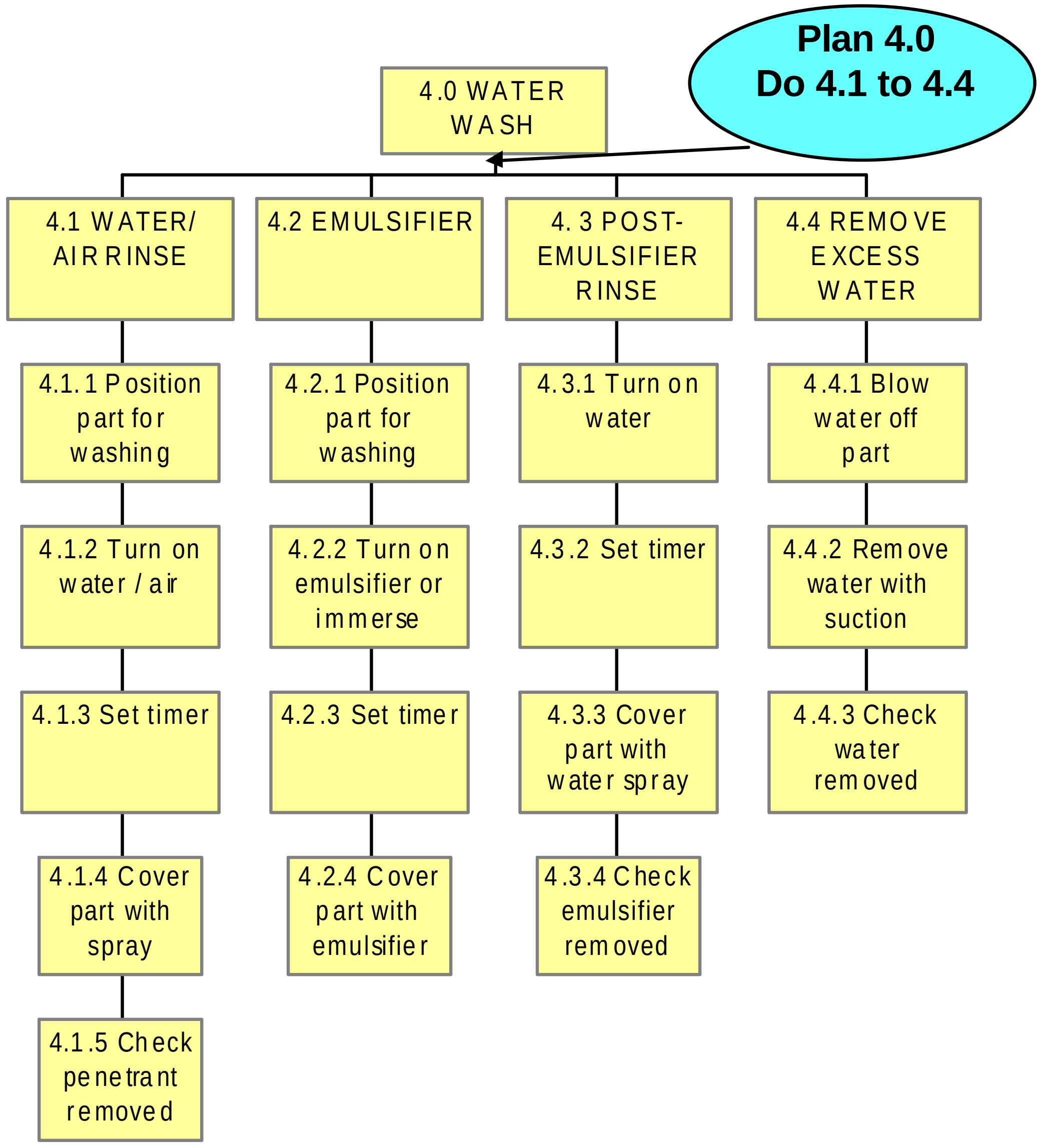

3.0 APPLY PENETRANT
Plan 3.0
Do 3.1 - 3.4 in order
3.1 SET UP
3.2 APPLY
3.3 CHECK PENETRANT COVERAGE
3.4 ALLOW DWELLTIME
3.1.1 Monitor penetrant parameters
3.2.1 Electro-static spray
3.3.1 Visually check for coverage
3.4.1Determine appropriate dwell time
3.2.1.1 Choose correct spray applicator
3.3.2 If not complete, return to 3.2
3.4.2 Allow penetrant to remain for dwell time
Plan 3.2
Do 3.2.1 or 3.2.2 or 3.3.3
3.2.1.2 Apply penetrant to surfaces
3.2.2 Tank application
3.2.2.1 Choose correct tank
3.2.2.2 Place part in tank for correct time
3.2.2.3 Remove part from tank
3.2.3 Spot application
3.2.3.1 Choose correct penetrant
3.2.3.2 Apply penetrant with brush etc.

3.0 Apply Penetrant

	Task Description	**Task Analysis**
3.1 Set-up	3.1.1 Monitor penetrant type, consistency (for electrostatic spray) or concentration, chemistry, temperature, level (for tank)	Are measurements conveniently available. Are measurement instruments well human-engineered? Do recording systems require quantitative reading or pass/fail?
3.2 Apply 3.2.1 Electrostatic spray 3.2.2 Tank 3.2.3 Spot	3.2.1.1 Choose correct spray gun, water washable or post-emulsifiable penetrants available. 3.2.1.2 Apply penetrant to all surfaces. 3.2.2.1 Choose correct tank, water washable or post-emulsifiable penetrants available. 3.2.2.2 Place in tank for correct time, agitating/turning as needed. 3.2.2.3 Remove from tank to allow to drain for specified time. 3.2.3.1 Choose correct penetrant, water washable or post-emulsifiable penetrants available. 3.2.3.2 Apply to specified areas with brush or spray can.	Are spray guns clearly differentiable? Can feeds be cross-connected? Can sprayer reach all surfaces? Are tanks clearly labeled? Is handling system ___________ to use for part placement? Does operator know when to agitate/turn? Does carrier interface with application? Is drain area available? Are spot containers clearly differentiable? Does operator know which areas to apply penetrant to? Can operator reach all areas with spray can/brush? Is handling systems well human-engineered at all transfer stages?
3.3 Check Coverage	3.3.1 Visually check that penetrant covers all surfaces, including holes. 3.3.2 Return to 3.2 if not complete coverage.	Can operator see penetrant coverage? Is UV light/white light ratio appropriate? Can operator see all of part? Can handling system back up to re-application?
3.4 Dwell Time	3.4.1 Determine dwell time for part. 3.4.2 Allow penetrant to remain on part for specified time.	Does operator know correct dwell time? How is it displayed? Are production pressures interfering with dwell time? Is timer conveniently available, or error-proof computer control?

3.0 Errors/Variances

Process measurements not taken.
Process measurements wrong.
Wrong penetrant applied.
Wrong time in penetrant.
Insufficient penetrant coverage.
Penetrant applied to wrong spots.
No check on penetrant coverage.
Dwell time limits not met.

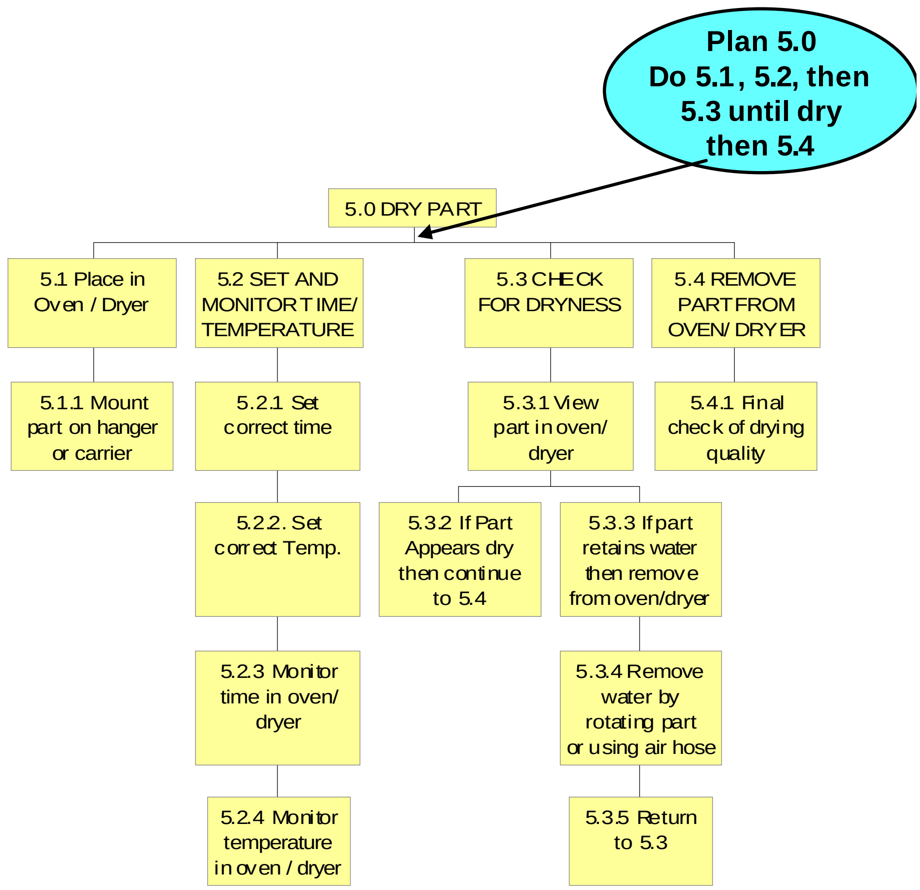

Plan 4.0
Do 4.1 to 4.4
4.0 WATER WASH
4.1 WATER/ AIR RINSE
4.2 EMULSIFIER
4. 3 POST-EMULSIFIER RINSE
4.4 REMOVE EXCESS WATER
4.1.1 Position part for washing
4.2.1 Position part for washing
4.3.1 Turn on water
4.4.1 Blow water off part
4.1.2 Turn on water / air
4.2.2 Turn on emulsifier or immerse
4.3.2 Set timer
4.4.2 Remove water with suction
4.1.3 Set timer
4.2.3 Set timer
4.3.3 Cover part with water spray
4.4.3 Check water removed
4.1.4 Cover part with spray
4.2.4 Cover part with emulsifier
4.3.4 Check emulsifier removed
4.1.5 Check penetrant removed

4.0 Water Wash

	Task Description	Task Analysis
4.1 Water / air rinse	4.1.1 Place part on bench 4.1.2 Turn water / air on 4.1.3 Set timer (2 minutes usual) 4.1.3 Cover part with spray 4.1.4 Check all penetrant removed	Bench height convenient for all tasks? Are water and air valves clearly marked and easily accessible? Is timer convenient to set? Is timer audible at wash bench? Can operator see and reach all points with spray in time available? Are bench and spray gun well suited to each other? Is there too much white light to see the remaining penetrant under UV light?
4.2 Apply Emulsifier	4.2.1 Place part on bench 4.2.2 Turn emulsifier on 4.2.3 Set timer 4.2.3 Cover part with emulsifier	Bench height convenient for all tasks? Is emulsifier valve convenient and well marked? Is timer convenient to set? Is timer audible at wash bench? Can operator see and reach all areas with emulsifier spray in time available?
4.3 Post-Emulsifier Rinse	4.3.1 Turn water on 4.3.2 Set timer 4.3.3 Cover part with water spray 4.3.4 Check all penetrant removed	Is water valve clearly marked and easily accessible? Is timer convenient to set? Is timer audible at wash bench? Can operator see and reach all points with spray in time available? Are bench and spray gun well suited to each other? Is there too much white light to see the remaining penetrant under UV light?
4.4 Remove excess water	4.4.1 Use air line to blow water off part 4.4.2 Use suction line to remove water from water traps in part 4.4.3 Check that all water has been removed	Is air line pressure correct, e.g. 5 psi? Is part at correct height for air line to reach all of part? Can operator see and reach all points with suction line? Does operator know where water tends to accumulate? Can operator see all points on part, even water traps?

4.0 Errors/Variances

Process measurements not taken.
Process measurements wrong.
Wrong wash selection (water/air vs. emulsifier)
Insufficient washing to remove penetrant
Excess washing flushes penetrant from cracks
Emulsifier not completely removed
Water not completely removed

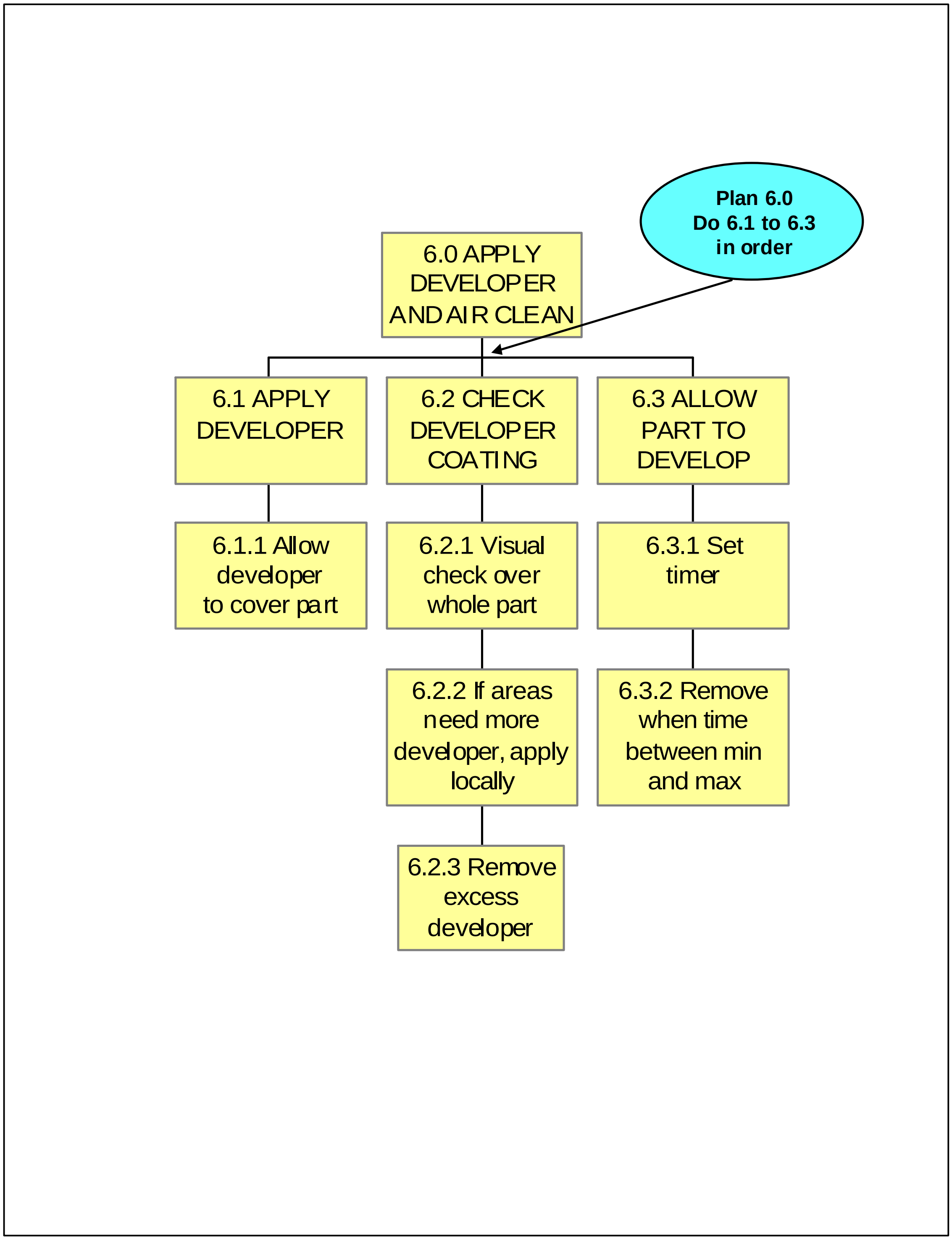


5.0 Dry Part

	Task Description	Task Analysis
5.1 Place Part in Oven / dryer	5.1.1 Mount part on hanger	Are carriers clean? Do carriers avoid metal to metal content? Can carrier prevent part from drying? Can carrier allow cross-contamination of processes? Is handling system well human-engineered?
5.2 Set and monitor time and temperature	5.2.1 Set correct time 5.2.2 Set correct temperature 5.2.3 Monitor time in oven / dryer 5.2.4 Monitor temperature in oven / dryer	Is time setting conveniently located and well human-engineered? Is temperature setting conveniently located and well human-engineered? Can time be monitored during other tasks with low error rate? Can time be monitored during other tasks with low error rate?
5.3 Check for Dryness	5.3.1 View Part in oven / dryer 5.3.2 If part appears dry then 5.4 5.3.3 If part retains water then remove from oven / dryer 5.3.4 Remove water by rotating part or using air hose 5.3.5 Return to 5.3	Can all areas of part be seen, or does operator have to remove part from oven to view? Can operator recognize areas retaining water? Is it safe and easy to remove part from oven / dryer? Can part be rotated on hanger with easy and without contamination? Is air hose convenient to use? Can operator monitor total air hose time and pressure to ensure they are below maxima?
5.4 Remove part from oven / dryer	5.4.1 Final check for drying quality 5.4.2 Remove part from hanger	Can all areas of part be seen, or does operator have to remove part from oven to view? Can operator recognize areas retaining water? Is it possible to recycle part through oven / dryer if not fully dry? Is handling system well human-engineered?

5.0 Errors/Variances

Water remains on part
Part contaminated in oven
Air hose use time or pressure limits exceeded


Plan 6.0
Do 6.1 to 6.3
in order
6.0 APPLY DEVELOPER AND AIR CLEAN
6.1 APPLY DEVELOPER
6.2 CHECK DEVELOPER COATING
6.3 ALLOW PART TO DEVELOP
6.1.1 Allow developer to cover part
6.2.1 Visual check over whole part
6.3.1 Set timer
6.2.2 If areas need more developer, apply locally
6.3.2 Remove when time between min and max
6.2.3 Remove excess developer

6.0 Apply Developer and Air Clean

	Task Description	Task Analysis
6.1 Apply developer	6.1.1 Blow developer over part	Does developer reach all areas of part? Does hanger interfere with developer coverage? Are displays and controls well-designed for operator use?
6.2 Check developer coating	6.2.1 Visual check over whole part 6.2.2 If areas need more developer, apply locally	Can operator view whole part? Can operator move part for viewing without contaminating part or removing developer film? Is local developer applicator well designed for operator use on part?
6.3 Air dry part	6.3.1 Set time and air pressure on hose 6.3.2 Blow excess developer off all areas of part 6.3.3 Check air hose time not exceeded	Are displays and controls well-designed for operator use? Can air hose be manipulated correctly by operator to reach all areas of part? Is pressure on air hose sufficient to remove developer from surface while still low enough to prevent removal from cracks? Does operator blow developer from all areas effectively? Is time limit visible / audible at operator position?

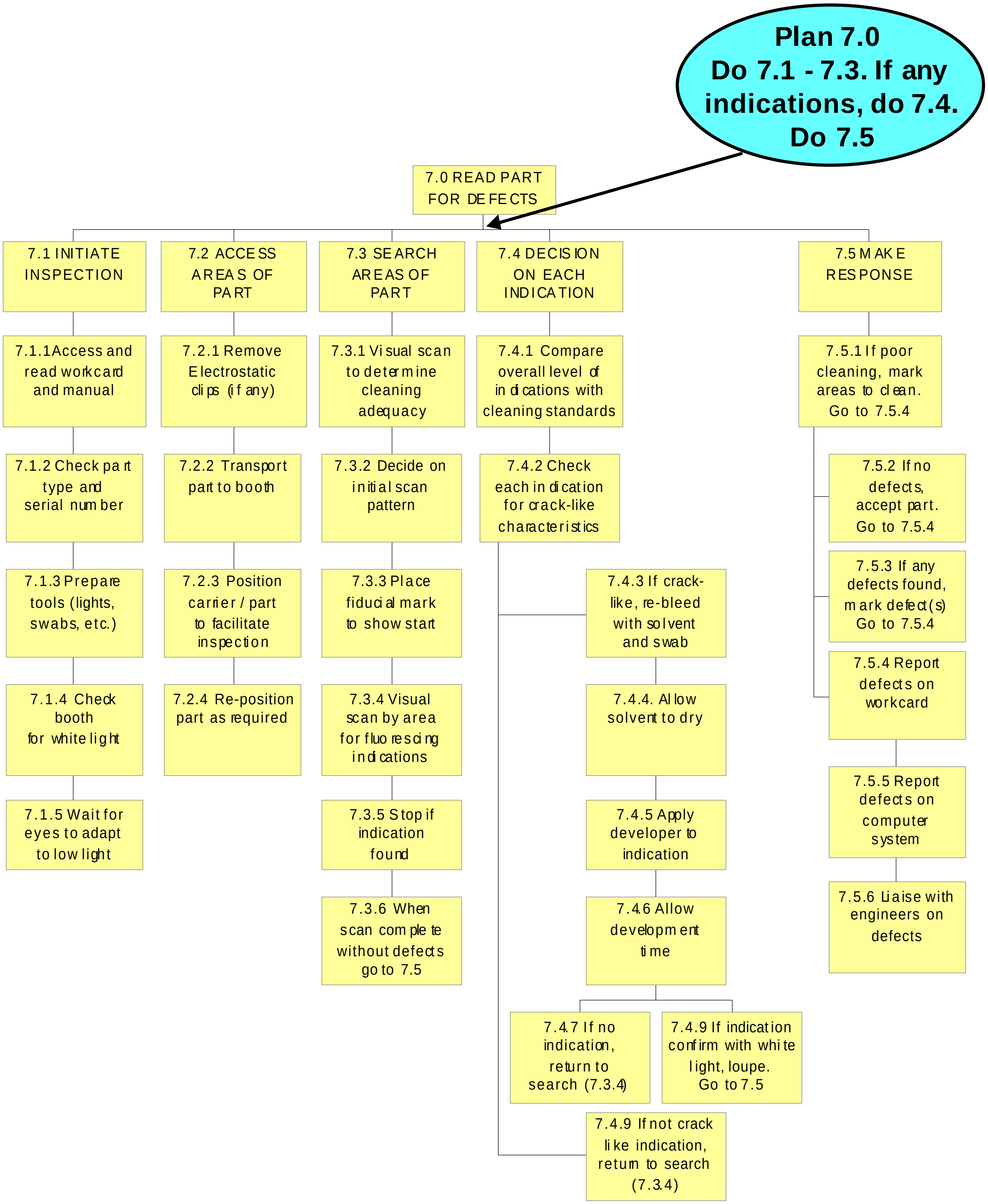
6.0 Errors/Variances

Developer not applied over all areas of part

Developer not removed from all surface areas

Part contaminated in developer / air dry process

Air hose use time or pressure limits exceeded


Plan 7.0
Do 7.1 - 7.3. If any indications, do 7.4. Do 7.5
7.0 READ PART FOR DEFECTS
7.1 INITIATE INSPECTION
7.1.1Access and read workcard and manual
7.1.2 Check part type and serial number
7.1.3 Prepare tools (lights, swabs, etc.)
7.1.4 Check booth for white light
7.1.5 Wait for eyes to adapt to low light
7.2 ACCESS AREAS OF PART
7.2.1 Remove Electrostatic clips (if any)
7.2.2 Transport part to booth
7.2.3 Position carrier / part to facilitate inspection
7.2.4 Re-position part as required
7.3 SEARCH AREAS OF PART
7.3.1 Visual scan to determine cleaning adequacy
7.3.2 Decide on initial scan pattern
7.3.3 Place fiducial mark to show start
7.3.4 Visual scan by area for fluorescing indications
7.3.5 Stop if indication found
7.3.6 When scan complete without defects go to 7.5
7.4 DECISION ON EACH INDICATION
7.4.1 Compare overall level of indications with cleaning standards
7.4.2 Check each indication for crack-like characteristics
7.4.3 If crack-like, re-bleed with solvent and swab
7.4.4. Allow solvent to dry
7.4.5 Apply developer to indication
7.4.6 Allow development time
7.4.7 If no indication, return to search (7.3.4)
7.4.9 If indication confirm with white light, loupe. Go to 7.5
7.4.9 If not crack like indication, return to search (7.3.4)
7.5 MAKE RESPONSE
7.5.1 If poor cleaning, mark areas to clean. Go to 7.5.4
7.5.2 If no defects, accept part. Go to 7.5.4
7.5.3 If any defects found, mark defect(s) Go to 7.5.4
7.5.4 Report defects on workcard
7.5.5 Report defects on computer system
7.5.6 Liaise with engineers on defects

7.0 Read Part

	Task Description	Task Analysis
7.1 Initiate Inspection	7.1.1 Access and read workcard and manual instructions 7.1.2 Check part type and serial number against workcard 7.1.3 Prepare UV light, white light, swabs, cleaning solvent, NAD 7.1.4 Check inspection booth for white light leaks 7.1.5 Wait until eyes adapt to low illumination level before inspecting 7.1.6 Position chair, lights, swabs, for ease of inspection	Is workcard available and well-written? Is manual available, readable and well-written? Is serial number easy to find and read? Have UV light, white light, been checked for correct output? Are all solvents approved? Are sufficient swabs available for task? Does booth admit white light? Are current standards adequate? Are standards met? Does inspector know how long to wait? Does inspector wait for correct time? Is layout ergonomically adequate?
7.2 Access each area of part	7.2.1 Transport part to reading booth and place on carrier 7.2.2. Remove Electrostatic clips (if on) 7.2.3 Position part / carrier to facilitate inspection 7.2.4 Re-position part as needed throughout inspection task	Is handling system well designed for inspector to use? Can part be positioned easily to bring eyes to correct position to inspect? Can part be re-positioned easily to bring eyes to correct position to inspect? Can inspector manipulate carrier, part, light(s), swabs, solvents, loupe together as needed?
7.3 Search areas of part	7.3.1 Visual scan to determine whether cleaning is adequate 7.3.2 Decide on initial scan pattern based on workcard and knowledge 7.3.3 Place fiducial mark to show start of inspection sequence 7.3.4 Visual scan area by area for indications fluorescing	Can inspector differentiate between indications likely to be cracks and false indications due to poor cleaning? Does inspector have an optimum scan pattern? Does inspector know where to put the mark? Can mark be seen during task? Does inspector follow the correct scan pattern? Are any areas missed? Can inspector see indications? Are white lights in field of view reducing indication visibility? Can inspector recognize indication?

	Task Description	Task Analysis
	7.3.5 Stop scan if indication found 7.3.6 When search complete with no defects, go to 7.5	Are there many false indications which slow task unacceptably? Does inspector return to correct point in search after re-bleed, NAD, white light use?
7.4 Decision on each indication	7.4.1 Compare overall level of fluorescent marks with cleaning standards to reject for cleaning 7.4.2 Check each indication for crack-like characteristics 7.4.3 If crack-like, re-bleed with solvent by wiping with solvent and swab 7.4.4 Allow solvent to dry and re-inspect 7.4.5 If indication does not bleed back, go to 7.4.9 7.4.6 Apply developer to indication 7.4.7 Allow developer to dry and re-inspect 7.4.8 If indication does not re-develop, return to search (7.3.4) 7.4.9 Confirm indication with white light and magnifying loupe	Does inspector have standards for good cleaning? Are they adequate? Is amount of solvent correct? Is inspector technique correct for re-bleed? Does inspector wait long enough for re-bleed solvent to dry? Does inspector try to use re-bleed waiting time for further scanning and potentially lose place in scan pattern? Does inspector return to correct point in scan pattern after re-bleed? Is amount of developer correct? Is inspector technique correct for developer? Does inspector wait long enough for developer to react? Does inspector try to use developer waiting time for further scanning and potentially lose place in scan pattern? Can inspector differentiate between cracks and other visually-similar indications? Does inspector return to correct point in scan pattern after NAD? Is inspector white light / loupe technique correct? Can inspector recognize indication as defect under white light? Are examples and/or limit standards of defects present at workplace? Does prior experience with larger cracks in other components bias inspector from reporting very difficult cracks? Does inspector return to correct point in scan pattern after white

	Task Description	**Task Analysis**
		light use?
7.5 Make response	7.5.1 If poor cleaning, mark areas of part needing better cleaning. Go to 7.5.5 7.5.2 If no defects then accept part. Go to 7.5.4 7.5.3 If defects found, mark crack(s) on part. Go to 7.5.4 7.5.4 Report outcome on workcard 7.4.5 Report outcome in correct detail on computer system 7.5.6 Liaise with engineers on defect details if required	Does marking show under UV light or must inspector use white light? Does marking show under UV light or must inspector use white light? Is workcard well designed for recording detail needed? Is computer interface and program well designed for recording detail needed? What are relations between inspection, engineering and production where pressures may cause decisions to be changed?

7.0 Errors/Variances

Workcard (or manual) not conveniently available
Workcard (or manual) gives inadequate detail for task
Workcard (or manual) poorly designed for user
Part not returned for cleaning when cleaning required
Part returned for cleaning when cleaning not required
Inspector does not wait long enough for dark adaptation
Contaminated areas of booth fluoresce causing visual masking of indications
White light penetrates booth and causes indications to be missed
White light for confirming cracks causes loss of dark adaptation
Layout of workplace inadequate for convenient physical movement of inspector
Manipulation of many objects simultaneously causes errors
Inspector does not locate indication
Re-bleed, NAD drying times not adhered to
Re-bleed, NAD times used for more inspection, causing inspector to lose place in scan pattern.
Contamination of part due to re-use of swab, or placing swab on contaminated surface
Inspector misinterprets indication: missed defect or false alarm
Workcard not suitable for recording all aspects of outcome
Computer system not suitable for recording all aspects of outcome
Pressures for production change inspection reporting standards

APPENDIX 2

Detailed Human Factors Good Practices for Each FPI Process

Table 9. Presentation of Human Factors Good Practices

Process	Good Practice	Why
Process Control	When recording process log, write measured values, not just "pass/fail" or sign off. Example: Record output of UV inspection light as 17,500 watt/m^2, not just "pass" for exceeding process standard.	1. Makes log recording less automatic, and therefore less prone to signoff error. 2. Allows capture of more useful process data. Example: deterioration of UV light can be seen by decreasing readings, so that a replacement can be ordered <u>before</u> light fails to meet standard.
Process Control	Allow good access room around all tasks and booths for maintenance.	1. If maintenance access is poor, maintenance may be postponed or even forgotten, reducing process control effectiveness. 2. Poor access increases the time required for maintenance, increasing process downtime.
Process Control	Ensure that operator follows good practices of washing or discarding gloves at different points in processing.	1. Contamination of gloves can spread to components, masking smaller cracks. 2. Penetrant on gloves will fluoresce in reading booth and cause glare to the inspector, reducing crack visibility.
Process Control	Reduce light levels around any areas where UV light is used.	1. Reduced light levels speed dark adaptation to improve indication visibility under UV light. 2. Reduced light levels minimize white light penetration of areas where tasks are carried out under UV light.
Cleaning	Maintain good communications between cleaning and FPI. Example: Weekly meetings, joint training, periods as "helpers" in each other's department. Example: Good process for returning components to cleaning.	1. Learning each other's jobs helps all operators work in a more knowledge-based manner. This can reduce errors and help to cope with unusual conditions. 2. If the return process is too informal, it may encourage poor cleaning. If the return process is too punitive, an unofficial process may be invented. Both can increase overall errors.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Cleaning	Ensure that system for matching components and paperwork is simple and visible. Example: Paired tags with easily readable numbers, 3 digits maximum and 2 digits better.	1. Simple, visible system reduces probability of parts going through wrong cleaning process. 2. Simple, visible numbers aid process logging, e.g. for timing in and out of tanks or dryers.
Cleaning	Ensure that the material handling system between tanks has controls which are conveniently located and which move in the correct sense. Example: Hoist controls move up to raise, and in the correct directions to move along the line.	1. If an operator moves a part in the wrong direction, metal-to-metal contact can occur, peening small cracks and making them more difficult to detect. 2. Movement errors can be prevented with controls located between waist and shoulder height, and which move in the correct sense.
Cleaning	Mark blasting processes which should not be used for rotating titanium components clearly, and train operators never to use them for titanium. Consider special markings for rotating titanium components (e.g. colored tags).	1. Abrasive blasting (e.g. grit, glassbeads) should not be used on rotating titanium components as they can peen small cracks, making them more difficult to detect. 2. Marking, labeling and training give increased redundancy, helping to reduce this error.
Cleaning	Have clearly visible and audible timers on each process, and train operators to use them.	1. Process timing can be critical so that using a clock on a wall or a wristwatch can produce timing errors that reduce cleaning effectiveness. 2. If times are easy to re-set, clearly visible and audible from all parts of the cleaning department, then operators can plan their work for efficiency while reducing errors.
Cleaning	Have clearly marked cleaning tools for different components, and train operators which to use. Example: Marked hangers for tools in different parts of the cleaning area.	1. Cleaning rotating titanium parts with some abrasives can obscure cracks and produce surface scratches. Both of these reduce probability of detecting cracks, particularly small cracks. 2. Clearly identified tools reduce the probability of such errors.
Cleaning	Design process indicator dials (e.g. temperature, water pressure) to be easily readable. Place them at eye height with appropriate lighting.	1. Indicators are only useful if they are easy to see and interpret. Errors will go unnoticed if dials are at knee height, or are difficult to interpret and record.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Cleaning	Train cleaners how to recognize when a part is adequately cleaned. This is best done by having FPI inspectors involved in the training.	1. Improperly-cleaned components cause re-cleaning delays, or reading errors. Unless the cleaners can recognize good cleaning (e.g. no dirt inside grooves or holes) they cannot ensure that cleaning is adequate. 2. FPI inspectors can show inspectors poor cleaning after penetrant application and help them recognize visible indications of poor cleaning.
Cleaning	Load components so as to avoid metal-to-metal contact.	1. Metal-to-metal contact can peen cracks, making them more difficult to detect, particularly small cracks.
Cleaning	Design hangers/baskets to prevent liquid collecting in components when transferring between processes.	1. Transferring liquids between processes prevents thorough liquid/component contact. 2. Transferring liquids between processes contaminates downstream processes.
Cleaning	If separate lines for each cleaning process, label lines as well as individual processes with clear, understandable and visible labels. Example: “Water cleaning” as well as “SPOP84”, both in 4 inch, contrasting lettering.	1. Sending parts through the wrong cleaning line is a rare error but one which can reduce cleaning effectiveness, causing delays for re-cleaning. 2. If lines have understandable as well as technical labels, errors are less likely and training is more rapid.
Cleaning	Label all process tanks and booths with clear, understandable and visible labels. Example: “Pre-wash solvent” as well as “Turco4181-L”	1. Errors in moving components to the wrong tank are rare, but can reduce cleaning effectiveness and cause cross-contamination of tanks. 2. If tanks have understandable as well as technical labels, errors are less likely and training is more rapid.
Cleaning	Design handling system using materials which do not absorb chemicals	1. Reduces contamination between tanks and contamination of components.
Cleaning	Specify line to be used and order of processes clearly on documentation, using both understandable and technical terminology.	1. Specification in understandable terms increases redundancy of information, therefore reducing errors. 2. Clearly marking the documentation for each component, e.g. using different colors of cleaning paperwork for different lines, reduces wrong-line errors and reduces training times.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Loading	Provide custom hangers for rotating parts, label them clearly and train loading personnel in how to choose them. If there are many, you can even specify which hanger on the process traveler.	1. Prevent metal-to-metal contact that can peen cracks over. 2. Allow easy rotation and movement throughout process, but especially in the reading booth. 3. Prevent wrong choices of hanger by training and labeling.
Loading	Ensure that each component is clearly marked with which FPI process is to be used. Example: separate lines for water-soluble and post-emulsification processes.	1. Using the wrong FPI process, while a rare event, can seriously reduce the visibility of cracks, particularly small cracks.
Loading	Provide convenient means for checking component serial number before component and paperwork are separated. Example: provide good lighting at the load component position and have place to hold the paperwork close to the component while serial number is checked.	1. Serial numbers can be difficult to read without good lighting, and difficult to compare to paperwork if long strings of numbers are involved. Mismatched serial numbers can waste processing time and inspection effort until the mismatch is discovered.
Loading	Provide well-designed job aid at loading to ensure all functions are completed. Example: simple checklist for steps, or list of steps mounted on wall.	1. The loading step is the most procedural in FPI, so can be supported by simple job aids. These help ensure that steps are not omitted in this repetitive function.
Loading	Design handling system, overhead hoists or roller conveyors, so that adjacent components cannot contact each other during processing.	1. If components hit each other the metal-to-metal contact can peen cracks, particularly small cracks, making them less visible. 2. As components tend to travel through the FPI process in batches, the handling system design should not rely on error-free human performance to prevent metal-to-metal contact.
Loading	Ensure that each component and accompanying paperwork can be re-matched easily. Example: paired tags attached to component and paperwork.	1. Good re-matching system ensures correct identification of often-similar components. This prevents errors that are only discovered later when serial numbers are re-matched.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Loading	Design cranes, conveyors and other handling systems to avoid metal-to-metal contact at all process stages.	1. The handling system and the component hanger must be designed together so that component does not contact metal, such as hooks or chains, throughout the FPI process. Metal-to-metal contact can peen small cracks, and scratch components, making inspection more difficult.
Loading	Design cranes, conveyors and other handling system components to ergonomics standards. Example: Roller conveyors should be at about 1 m from ground for safe lifting. Example: Controls should be located between waist and shoulder height (1-1.7 m) and should move in the same sense as the component.	1. Ergonomic design prevents injuries and promotes safe use. 2. Poorly designed equipment encourages operators to use unapproved shortcuts that can reduce inspection effectiveness. 3. Controls should be operable without reaching, bending or stretching for safe use. 4. Controls should move in the expected direction: up for on or raise; left for left movement, etc.
Loading	Provide good equipment and training to allow operator to judge whether cleaning is adequate. Example: Good lighting and clean swabs to check for dirt or oil in holes, grooves, dovetails or firtrees.	1. Ensures that processing time is not wasted on poorly-cleaned components. Discovery of poor cleaning at the reading booth disrupts the schedule and wastes inspector's time. 2. Rejection before processing prevents inspectors from trying to inspect a poorly-cleaned component, which could lead to missed indications.
Loading	Design handling system and hangers to ensure that penetrant, emulsifier, water and developer can reach all parts of the component. Note: This may mean that component needs to be moved on hanger or conveyor during processing.	1. If the hanger or conveyor prevents liquids from reachng any part of the component, the subsequent inspection will not be complete.
Loading	Design handling system and hangers so that contamination between processes is minimized. Note: This may mean that component needs to be moved on hanger or conveyor during processing.	1. If liquids can be retained by the component or hanger, subsequent processes will be contaminated. This can reduce process purity, and/or make reading more difficult and error prone.
Apply penetrant (spray)	Train operators to move spray gun and component so that all areas can be reached.	1. Incomplete coverage can cause cracks to be missed where no penetrant was applied.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Apply penetrant (spray)	Make the spray gun easier to maneuver by suspending or balancing the weight of the hose. Also choose the lightest and most flexible hose.	1. A more manageable spray gun helps the operator reach all areas of the component, preventing missed cracks where no penetrant was applied. 2. Choosing a light and flexible hose, and balancing its weight makes the gun move maneuverable.
Apply penetrant (tank)	Design process indicator dials (e.g. temperature, water pressure) to be easily readable. Place them at eye height with appropriate lighting.	1. Indicators are only useful if they are easy to see and interpret. Errors will go unnoticed if dials are at knee height, or are difficult to interpret and record.
Apply penetrant (tank)	Label all process tanks and booths with clear, understandable and visible labels. Example: “Pre-wash solvent” as well as “Turco4181-L”	1. Errors in moving components to the wrong tank are rare, but can reduce cleaning effectiveness and cause cross-contamination of tanks. 2. If tanks have understandable as well as technical labels, errors are less likely and training is more rapid.
Apply penetrant (spot)	Ensure that the containers for the two penetrant systems are clearly differentiable. Example: Different colored cans, can placement on opposite sides of booth, clear and understandable labels on can.	1. Error of using the wrong can may reduce visibility of cracks, particularly small cracks. 2. The more ways in which the can is different, the more redundancy is available to prevent this error. Small, technical labels (e.g. SPOP084) are not sufficient to eliminate this error.
Apply Penetrant (spray)	Design the drum-to-spray gun connections so that each spray gun can only be connected to the correct drum. Example: Different sized fittings, reversal of male and female coupling are on line.	1. Applying the wrong penetrant can reduce crack visibility, particularly for small cracks. 2. Physically-different fittings reduce the probability of a wrong connection to zero.
Apply Penetrant (spray)	Make spray guns for water-soluble and post emulsifier penetrants clearly distinguishable. Example: Different designs of gun, different colors of gun, holders on different sides of spray booths, large labels visible under UV light.	1. Error of using the wrong spray gun can reduce visibility of cracks, particularly small cracks. 2. The more ways in which the spray guns are different, the more redundancy is available to prevent this error. Small, technical labels (e.g. SPOP084) are not sufficient to eliminate this error.
Apply Penetrant (spray)	Perform spraying under UV light with a minimum of white light, e.g. walk-in booth with UV light only.	1. Fluorescence of penetrant makes it easier to ensure complete penetrant coverage of part. This reduces the probability of missing a crack because it never received penetrant.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Apply Penetrant (spray)	Locate process gauges, e.g. for line pressure or temperature, between waist and shoulder height and design them to be easy to read under UV illumination. Example: Temperature gauge marked with acceptable range in fluorescent orange.	1. Before each application process gauges should be checked to ensure process is in control. The easier the gauges are to check, the more often this rule will be followed.
Apply Penetrant (spray)	Ensure that timer system for penetrant application is flexible enough to handle real operations. Example: Separate timing for each component or timing for clearly-marked batch of components.	1. A single timer for penetrant application cannot be used for multiple components unless they are carefully and visually batched. Multiple timers or large display board for recording times are required if parts are not batched.
Apply Penetrant (spray)	Locate electrical controls (e.g. for UV and white lights, timers) where they are clearly visible and clearly labeled.	1. Dark adaptation can be ruined by inadvertent use of white light. Good location and labeling of controls helps prevent this error.
Apply Penetrant	Keep extraneous hoses and spray guns (e.g. for cleaning booth) out of spray booth.	1. Any extraneous equipment can be used by mistake instead of the correct equipment, potentially stopping the processing of a component. 2. The less equipment that is in the spray booth the easier it is to provide visual control over the entrance of unapproved substances.
Water Wash	Design wash booth so that component can be washed between shoulder and elbow height.	1. Convenient positioning of the component helps ensure that all penetrant or emulsifier is removed, improving visibility of cracks and reducing false indications.
Water Wash	Provide a clearly visible and audible timer for emulsifier dwell time. Example: Large clock on wall with sweep second hand and loud signal when complete.	1. Emulsifier timing is critical and needs to be done in seconds, not minutes. Excess time in the emulsifier can reduce crack detectability, particularly for small cracks. 2. A large visible timer, easily set in seconds, helps operators plan their spraying and waiting. A loud end-signal ensures that operator interrupts other tasks to begin washing the component.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Water Wash	Perform washing under UV lighting, with minimal white light.	1. Areas of the component retaining penetrant are much easier to see under UV lighting. This leads to more thorough washing, improving crack visibility.
Water Wash	Train operators to move wash gun and component so that all areas can be reached.	1. Incomplete coverage can cause cracks to be missed where no penetrant was applied.
Water Wash	Make the wash gun easier to maneuver by suspending or balancing the weight of the hose. Also choose the lightest and most flexible hose.	1. A more manageable wash gun helps the operator reach all areas of the component, preventing missed cracks where penetrant was not removed. 2. Choosing a light and flexible hose, and balancing its weight makes the gun move maneuverable.
Water Wash	Design displays for water and air pressure to be easily legible under UV light. Locate them at eye height.	1. If water and air pressure are incorrect, too much penetrant may be washed from cracks, making them less easy to detect. 2. Convenient and legible displays help ensure that they are used for every component processed.
Water Wash	Provide air line and suction hose to remove excess water, particularly where water can accumulate in a component. Ensure that airline and suction hose do not have metal nozzles.	1. Water accumulation in pockets of a component will not be dried in oven, leading to incomplete developer coverage, which reduces crack visibility. 2. Using plastic or rubber nozzles on air hose and suction hose reduces risk of metal-to-metal contact which can peen cracks, particularly small cracks.
Water Wash	Train operators to provide complete coverage of all components in emulsifier application, wash and water removal.	1. Even with good tools and work area, training is important to ensure full coverage of each type of component, enhancing crack visibility. 2. Operator knowledge of particular components helps them perform their tasks more thoroughly.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Drying	Either provide a system for timing each component in drying and developing, or use clearly-marked batches of components with a single timer for each process. Example: Use a display board to write in and out times of individual components. Example: Use colored tags to visually indicate batches, and time each batch as a single item.	1. Timing of drying and developer application must be well controlled for maximum visibility of cracks. 2. One timer (or recording) per component is required if components flow individually. If components are batched, a single timer can be used for the whole batch, but the batch must have a clear visual indication to avoid errors.
Drying	Train operators to move components in dryer if water can accumulate in component.	1. If water pocket in component is not completely dried, developer will not have complete coverage, with potential for missing cracks.
Drying	Controls and displays for dryer temperatures should be at eye height and be easy to set/read.	1. Dryer temperature must be controlled to ensure correct processing for maximum crack visibility. 2. Well-designed displays at eye height help ensure that dryer temperature is checked for each component processed.
Dryer	When developer is applied to a component, ensure even and gentle coverage of all areas.	1. Developer powder penetrates holes, etc. well, but component must be completely immersed in developer cloud for full coverage. Incomplete coverage reduces crack visibility significantly.
Dryer	Make low pressure air hose available to blow off excess developer powder.	1. Excess developer powder will contaminate reading booth. 2. Excess developer powder can distract from the search process in reading booth.
Reading	Keep reading booth separate from inspector's "home" area.	1. Prevents accumulation of personal possessions in reading booth. This reduces distractions, prevents penetrant contamination, and gives visual control over entry of non-approved substances into reading booth.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Reading	Provide timer in booth to indicate dark adaptation time. Train inspectors that at least 2 minutes adaptation is needed after every white light exposure. Note: Other work can be done during this time provided the inspector does not view bright objects.	1. Dark adaptation is essential to defect visibility. Without dark adaptation only large indications can be seen. 2. The dark adaptation process is widely misunderstood. Many inspectors believe that a time much shorter than the recommended time applies to them. After about 8 minutes in darkness, the eye is about 100 times as sensitive as when first entering a darkened room. 3. Inspectors are eager to get on with the reading, and often overestimate how much adaptation time has passed.
Reading	Ensure that other objects in the reading booth are not fluorescent. Example: inspector's clothing, inspection paperwork.	1. Any object fluorescing under UV light becomes a glare source which decreases the visibility of defects, particularly small defects.
Reading	If there is a computer terminal in the display booth, provide a rapid means of lowering its brightness when the booth is darkened. Example: Flip down dark plastic screen, or two-position brightness switch.	1. Bright computer screens can provide a source of glare, and reduce dark adaptation. Both will reduce defect visibility, particularly for small defects. Note: The dimmer screen will be adequately visible when the eye is fully adapted.
Reading	Provide surface for inspecting which is soft and easy to clean. A modern example would be the black plastic ………………..(brand name)	1. Prevents physical damage to components from contact with surface. 2. Reduces chance of component falling off inspection surface. 3. Prevents penetrant contamination which reduces defect visibility, particularly for small deflects.
Reading	Choose materials for hangers that are yielding but will not retain penetrant.	1. Prevents physical damage to components from contact with hanger. 2. Prevents penetrant contamination that reduces defect visibility, particularly for small deflects.
Reading	Ensure that all tools, such as UV light, white light, magnifier, ruler, cannot make metal-to-metal contact with the component. Plastic coverings are recommended, but they must be maintained.	1. Metal-to-metal contact can peen cracks, especially smaller cracks, making them less visible. 2. Metal-to-metal contact can scratch the component, giving a false indication in future fluorescent penetrant inspections.

Table 9. Presentation of Human Factors Good Practices

Process	Good Practice	Why
Reading	Wear UV-absorbing glasses at all times when UV light is on.	1. UV light can cause cataracts if prolonged. 2. UV absorbing glasses reduce any diffusing glare in the eyeball, and thus enhance defect visibility, particularly for small defects.
Reading	Use markers on component to show where inspection started and how inspection is progressing. Makers include approved pens and tapes for starting marker, and movable sticker for progress marker. The inspector's hand which is steadying the component can be used as a movable marker if it does not contaminate the part, and if it is never needed for other activities.	1. Rotating components have no visually-obvious starting point, so that a start marker is needed to show when each circuit of visual search has been completed. If no marker is used, part of the component may not be inspected. 2. As search progresses, any interruption can cause inspectors to lose their place in the search, leading to parts of the component not being inspected. Interruptions are not just external but can include applying de-bleed solvent or NAWD and waiting for it to complete its action.
Reading	Have low pressure air in the reading booth to blow away fluorescing dust specks.	1. Dust specks can adhere to the component surface where they become false indications which slow and distract the search process. 2. Gentle air blowing is preferable to either hand-wiping or mouth blowing as it prevents surface contamination.
Reading	Use a consistent and systematic search strategy in inspecting the component.	1. A good search strategy ensures complete coverage, preventing missed areas of inspection. 2. A consistent strategy will be remembered better from component to component, reducing memory errors.
Reading	Inspect holes in components (e.g. bolt holes) with a diffuser behind the hole rather than the UV light itself.	1. Looking through a hole directly at a UV source can harm the eyes. 2. A diffuse source reflects UV lights equally around all parts of the hole internal diameter, so that only the eyes need to move around the hole and not the UV light source.
Reading	Train inspectors in a consistent strategy of eye movement for inspecting holes and blade dovetails/firtrees.	1. A consistent search strategy ensures complete converge of each hole or dovetail/ firtree. This prevents missing areas of high physical stress where small cracks are more likely.

Table 9. Presentation of Human Factors Good Practices		
Process	**Good Practice**	**Why**
Reading	Ensure that inspectors allow the correct time for an indication to de-bleed after swabbing with solvent.	1. Inspectors underestimate the time needed for de-bleeding. 2. Inspectors overestimate the time which has elapsed since solvent applied. Note: Both reasons result in an indication not bleeding back sufficiently for detection during the inspector's viewing time.
Reading	Eliminate white light leaks into reading booth. Note: Even if the 2 lux standard is met at the surface of the component, there may still be white light sources visible from the inspector's position.	1. White light causes loss of dark adaptation, which reduces the visibility of defects, particularly small defects.
Reading	When an indication is found under UV light, mark it temporarily and complete UV inspection before checking the indication under white light.	1. Every time a white light is used in the booth, dark adaptation is lost, which reduces the visibility of defects, particularly small defects.
Reading	Provide both fixed area and portable spot UV illumination in the reading booth. The area light may be UV fluorescent tubes at ceiling level.	1. A large diffuse UV source provides unchanging, even illumination of the component, while a spot UV source provides brighter illumination that can be aimed as needed. This combination allows the inspector to obtain appropriate illumination at any point on the component.
Reading	Provide easily-adjustable seating for the inspector.	1. Comfortable seating increases inspection effectiveness. Easy adjustability allows inspectors to keep their eyes at the correct location throughout inspection.
Reading	If the inspection is performed on a table, allow knee room under the table. Do not use the space under the table for shelves or storage.	1. Unless inspectors can put their knees under an inspection table, they will either twist sideways on their chair, or stand and bend over the table. Both reduce comfort and so result in decreased performance. 2. Storage areas below table height reduce the ability to visually control the contents of the inspection booth.

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Process	Good Practice	Why
Reading	Provide a magnifier of sufficient power that is easy to use so that indications can be checked under white or UV light. A good magnifier is 5X – 10X, with as much eye relief as possible. An alternative is a magnifier attached to the inspector's glasses, which can be swung into the line of vision as needed.	1. Confirmation of some indications, particularly small ones, requires magnification to see the morphology of the indication. For example, under magnification a scratch is distinguishable from a crack. 2. Convenience is essential to encourage the inspector to use the magnifier on all indications. Good eye relief allows the inspectors to view the indication with less postural difficulty. Magnifiers attached to glasses (e.g. as used by dentists) are perhaps the most convenient in use. They would also help ensure that UV absorbent glasses are always worn.
Reading	Place swabs, solvent, NAWD and magnifying lamps where they can be reached and used easily during inspection.	1. Placing items conveniently causes minimum disruption to the search process and ensures full coverage of component. 2. If items are conveniently located, they are more likely to be used every time they are needed.
Reading	Design hanger and suspension system for easy vertical movement. Example: balance hoist for instant positioning.	1. The easier it is to move the component vertically, the less extreme postures will be needed to inspect it fully. This helps ensure full inspection coverage.
Reading	Provide a well-designed job aid such as a workcard for each component. Example: Workcards with details of component nomenclature, places where defects are most likely and past defect history of these components. This can be done via paper copy or computer program.	1. A good workcard will define the inspection level and any special use of solvent or NAWD. 2. A good workcard can capture inspection knowledge from a variety of sources to allow inspectors to develop better search patterns and defect expectations.
Reading	Design reporting system to identify defect in sufficient detail. Example: standards for making defect location or component and convenient means to explain indication to subsequent stages.	1. Standard and comprehensive reporting reducing errors in interpretation of indications and ensures better final decisions. 2. If reporting is inconvenient, e.g. insufficient space on form or computer field to explain indication, inspector will have to curtail the explanation, affecting decision accuracy.

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Process	**Good Practice**	**Why**
Reading	Provide visual test of dark adaptation in reading booth. Example: fluorescent eye chart at appropriate distance from inspector.	1. Gives inspector immediate indication that proper level of adaptation has been reached. 2. Proper adaptation improves defect visibility, particularly for small cracks.
Reading	Train inspectors to use de-bleed solvent on all indications which could conceal a crack.	1. Swabbing with approved solvent effectively removes penetrant from large areas. When penetrant is removed, a crack could be revealed beneath the penetrant. De-bleeding will confirm the indications as a crack rather than surface contamination.
Reading	Train inspectors to wait for a long enough interval after swabbing with solvent for any crack to de-bleed and re-appear. The correct time can be marked prominently on the solvent container.	1. A crack indication will not re-appear instantly. As time elapses, any true indication will become stronger as penetrant de-bleeds towards the surface. 2. Inspectors often underestimate the time needed for a crack indication to fully de-bleed.
Reading	Train inspectors to allow sufficient time for NAWD applied to an indication to fully develop. Mark the correct development time prominently on the NAWD container.	1. A crack indication will not re-develop immediately. Often several minutes are required for full development to render crack adequately visible. 2. Inspectors tend to underestimate the time required for re-development. Alternatively, visual search of new areas is continued during re-development, leading to memory errors concerning inspection coverage.
Reading	Provide easily attached holder or hanger for portable UV light for when both of the inspector's hands are needed for other tasks.	1. Allows consistent positioning of UV light for each circuit of a rotating component. 2. Allows inspector to use solvent, swabs, magnifying lenses while still holding component in correct position.
Reading	Provide attachment on component hanger to stop component swinging during inspection. Example: quickly attached clamp to booth structure, or even good hand grip on holder.	1. Frees one of inspector's hands for other tasks. 2. Encourages inspector to move around component to obtain best visibility of indications in different areas.

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Process	**Good Practice**	**Why**
Reading	Always use swabs (e.g. Q-tips) for applying de-bleed solvent. Always throw away swabs after single use.	1. Swabs provide correct amount of solvent. Too much solvent can be applied if sprayed or washed on, reducing visibility of cracks, particularly small cracks. 2. A clean swab each time prevents spreading of penetrant which can potentially conceal indications.
Reading	Use glares when handling components through processing and remove or replace glares for reading.	1. Contamination of gloves with penetrant or other chemicals can be transferred to component. This causes distracting glare from penetrant, reducing crack visibility. 2. Contaminated gloves also fluoresce to produce glare that can reduce visibility of cracks, particularly small cracks.